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By W. A. Leary, E. S. Taylor, C. F. Taylor,
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SUMMARY

A machine has been developed to study the ignition delay of fuels by means of a rapid adiabatic compression. The essential features of this machine are:

(1) The compression is completed in about 0.006 second

(2) Provision is made for obtaining simultaneous records of piston motion and cylinder pressure

(3) The combustion cylinder is unlubricated

The rapidity of the compression renders the apparatus suitable for investigating the ignition delays of fuels under conditions of compression comparable with those existing in the end gas of spark-ignition internal-combustion engines.

Simultaneous records provide means for correlating piston position and pressure at any instant during, or after, the compression, and the absence of lubricant on the walls of the combustion cylinder ensures against contamination of the explosive mixture by oil vapors.

The apparatus opens new possibilities for studying the detonation characteristics of fuels. Also, the tests can be conducted on a few milliliters of fuel. This feature should be invaluable in the case of pure compounds which are available only in small amounts.

INTRODUCTION

In order to study self-ignition phenomena under conditions more easily controlled than those existing in an engine, a number of compression machines have been built in which a single, rapid compression and subsequent self-ignition could be obtained. A brief description of these machines, in which their advantages and limitations are discussed, is given in appendix A.

A compression machine suitable for studying short ignition delays should have the following features:

(1) The compression should be as rapid as possible

(2) There should be no rebound of the piston at the end of the stroke

(3) The working cylinder should be unlubricated

(4) There should be means for recording gas pressure and piston position as a function of time

(5) A means should be provided for varying the compression ratio and the initial pressure and temperature of the explosive mixture

A rapid compression is necessary in order to reduce heat losses to the extent that the adiabatic process may be closely approximated. It is also essential that the compression be rapid if fuels having short ignition delays are to be investigated.

Piston rebound at the end of compression should be avoided in order to prevent the attendant adiabatic cooling of the cylinder contents with consequent errors in measurements of delay periods and ignition temperatures. The contamination of the explosive mixture by lubricant vapors also should be avoided because it is another source of uncertainty.

Pressures in the cylinder should be recorded as a function of time in order that the pressure-time curves may be compared, delay periods measured, and combustion phenomenon, such as pressure waves, studied. A record of piston motion should also be provided so that the position and velocity of the piston at any instant can be determined. The piston record will show whether or not the piston bounced at the end of compression.

With these considerations in mind, a machine has been constructed which, as a first requirement, compresses so rapidly that short delay periods can be investigated. The machine also possesses the other features listed as desirable. The present compression time is about 0.006 second which is equivalent to the time of the compression stroke of an internal-combustion engine running at about 5000 rpm. The machine, moreover, is rugged and no mechanical failures have been encountered as yet. The upper or driving-pressure cylinder was designed to work at 2000 pounds per square inch, but the maximum pressure used to date has been only 500 pounds per square inch. These facts encourage the expectation that the compression time may be decreased to about one-half the present value should this reduction appear desirable.

This machine has been used in an investigation of the compression-ignition characteristics of four fuels. The results of this research are reported in reference 1.

The authors are indebted to J. R. Diver (reference 2) for making a preliminary survey of the field and investigating various methods of preventing piston rebound, to W. K. Bodger and especially to H. A. Lang for making the necessary design calculations and drawings, and to O. W. Welles who made significant contributions to the development of the apparatus (reference 3).

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DESCRIPTION OF RAPID COMPRESSION MACHINE

A cross-sectional view of the rapid compression machine is shown in figure 1. The principal parts of the machine are: the upper cylinder (1), the lower cylinder (2), the cushion chamber (3), the combustion cylinder (4), the piston (5), and the poppet valve (6). Complete details of construction, including dimensions, are given in appendix B.

OPERATION OF THE RAPID COMPRESSION MACHINE

The machine is used as follows: the upper cylinder is sealed by drawing up the poppet valve by means of a screw jack (7) which bears on shear pins (8) passed through a hole in the valve stem. With the piston at the top of its stroke (as shown in fig. 1), a mixture of fuel and air is admitted to the combustion cylinder. A charge of nitrogen at 500 pounds per square inch is then introduced in the upper cylinder and a similar charge at 110 pounds per square inch is admitted to the cushion chamber. Small adjustments have to be made in the cushion pressure, however, in order to compensate for the decrease in friction due to wearing of the lead bands on the piston skirt; but the main objective in varying the cushion pressure is not so much to keep the compression time meticulously constant as to ensure proper seating of the piston. A change of 2 or 3 pounds in the cushion pressure might mean the difference between a smooth seating of the piston or one accompanied by a severe mechanical shock. At the end of the stroke the cushion pressure rises to approximately 800 pounds per square inch and since a sensitive gage is used to adjust the initial pressure, protection can be provided by inserting in the gage line a valve ((78), fig. 2) which is always closed immediately before firing the apparatus. A check valve at the entrance port ((79), fig. 1) prevents reverse flow of nitrogen from the cushion chamber to the nitrogen cylinder.

The poppet valve is then suddenly opened by dropping a weight on the valve stem and shearing off the pins. The violent release of pressure causes the piston to descend rapidly; the central part, or snout (9), compressing the mixture in the combustion cylinder, and the part exterior to the combustion cylinder compressing the entrapped nitrogen in the cushion chamber. The rapid build-up of pressure in the cushion chamber prevents severe mechanical impact of the piston at the end of its stroke for, when properly adjusted initially, this pressure reaches a peak value sufficient to reduce the piston velocity to nearly zero. Ports (10) in the piston then come into register with ports (11) in the lower cylinder sleeve (12) and the cushion pressure is released. This allows the driving pressure to hold the piston to its seat and when the pressures are properly adjusted, no rebound occurs. The piston also remains tightly seated during the explosion process.

The piston is returned from the end of its stroke by removing the combustion cylinder head and pushing up the piston with the aid of a piece of hard wood, rounded on the upper end to fit the piston snout, and a hydraulic jack.

DESCRIPTION OF AUXILIARY APPARATUS

Photographs of the complete apparatus are shown in figure 3 and a schematic diagram appears in figure 2. In this diagram the component parts are rearranged from their actual relative positions for the sake of clarity. The compression machine (36) was mounted on a heavy steel table which was secured to an iron bedplate. A scaffold carried the weight (37) used for shearing the poppet-valve pins. The weight was constrained to slide in a guide and was supported by a rope which was secured at a bracket (38). A trigger (39), to which a lanyard was made fast, was used to trip the weight from the control panel which may be seen in the foreground of the top photograph in figure 3. A stop ((41), fig. 2) in the rope engaged with another bracket (42) at the end of the fall and prevented the weight from descending any farther than was necessary for shearing the pins.

Pressure for operating the machine was supplied by nitrogen cylinders (43) through flexible pressure lines. The driving and cushion pressures were measured by gages (44) and (45) mounted on the control panel and connected to the cylinders by means of flexible pressure tubing.

Temperature Control

The combustion cylinder was maintained at a uniform temperature by means of a water jacket connected with a closed heating system. A header tank (46) containing two electric immersion heaters (47) and an adjustable thermostat (48) supplied hot water for the system. The water was circulated through the combustion-cylinder jacket, through a small jacket on the line (49) connecting the fuel-air mixing tank with the combustion cylinder, thence through the jacket on the fuel-air mixing tank (50), and finally back to the header tank. A small electric centrifugal pump (51) was used for this purpose. The line connecting the interior of the fuel-air mixing tank to the combustion cylinder was jacketed in order to prevent any condensation of the fuel on the way to the combustion cylinder. A mercury thermometer (52) placed near the pump outlet was used to give the temperature of the circulating water. The temperature here was about 1° F higher than the temperature of the water leaving the cylinder jacket, but provision was made for inserting thermometers directly at the inlet and outlet of the cylinder jacket should this appear to be necessary. The thermostat kept the water temperature constant within ±1° F.

An auxiliary steam heat exchanger (53) was installed in the circuit in order to bring the apparatus to temperature rapidly. Otherwise the electric heaters were sufficient. A small amount of rust inhibitor was added to the circulating water to keep the metallic surfaces clean.

Fuel-Air Mixing Tank

A sectional view of the fuel-air mixing tank is shown in figure 4. The tank consisted of a water-jacketed cylinder closed at both ends, a sliding piston, and a motor-driven fan. There were five openings in the bottom of the tank - an air entrance, a fitting in which a cork was placed to act as a safety valve, an exit for the mixture, a thermometer fitting, and a manometer connection. The piston was made from a metal disc and a leather cup washer was clamped at the rim. When the tank was empty the piston rested on the bottom of the cylinder on the lugs (54) but rose slowly when air was admitted. A weight of about 75 pounds was placed on the piston rod in order to provide sufficient pressure to make the leather seal effective while the tank was being filled. The pressure was read from a mercury manometer mounted by the side of the tank.

When the piston reached the upper limit of its travel, a small brass tubing fitting (55), screwed into the piston, protruded through a hole in the cylinder head. This fitting contained a small neoprene diaphragm, clamped in compression, through which liquid fuel was injected by means of a hypodermic needle. In order to keep the fitting lined up with the hole, the piston rod was made square in cross section and was passed through a square guide (56) on the top of the cylinder. With the piston at "top center," the cylinder was airtight in spite of innumerable punctures in the diaphragm, and mixing and vaporization of the fuel took place under conditions of no leakage so that a definite fuel-air ratio was accurately obtained.

After introducing the fuel, the mixture was thoroughly agitated by means of the fan which was driven by a small three-phase induction motor mounted in a well at the bottom of the tank. This type of motor was used in order to avoid sparks which would inevitably lead to an explosion. The motor well was connected with the tank through the shaft hole which was three times the diameter of the motor shaft. A valve was placed in the bottom of the well for purposes of flushing.

Since it was important that the volume of the mixing tank be accurately known, the motor, fan and fittings were immersed in water and their volumes measured by the displacement method. The parts were then thoroughly dried out and assembled. It was also necessary to prevent any contamination of the air as a result of evaporation of oil from the motor bearings; therefore a motor having ball bearings was selected and these were thoroughly flushed out with gasoline and dried. The operation of the motor without oil was satisfactory, because the fan was used only intermittently.

After filling the tank, the exit valve was opened and the weighted piston descended slowly causing the mixture to flow into the combustion cylinder. Any leakage of mixture past the tank piston during this process had no effect on the fuel-air ratio since the fuel and air were now in the form of a homogeneous mixture. No lubrication was used on the walls or piston of the mixing tank, although the leather cup washer was softened with neat's-foot oil during the process of construction.

The mixing tank was insulated with a 1-inch layer of magnesia covering to diminish heat losses. The temperature of the water jacket was kept sufficiently high to ensure complete evaporation of the fuel.

The fuel-air ratio was varied either by changing the amount of fuel injected or the quantity of air pumped into the mixing tank. The entire contents of the tank were circulated through the combustion cylinder to reduce dilution caused by the initial air in the combustion cylinder, and to diminish this dilution further, the combustion cylinder was first exhausted to 2 inches of mercury absolute by means of a hand-operated vacuum pump ((77), fig. 2). The mixture was admitted immediately after the cylinder had been evacuated, and when the charging was completed, the inlet and exit valves were closed and the contents sealed off at atmospheric pressure. The barometer was read before each run, thus determining the initial pressure.

The volume of the tank was 1.10 cubic feet and the volume of the combustion cylinder was 0.00564 cubic foot. Pressures of from 38 to 46 inches of mercury absolute were used in the tank in preparing mixtures so that the ratio of the weight of mixture passed through the cylinder to that retained for the test was at least 250:1.

The tank was flushed with clean, dry air before preparing a new mixture, by allowing the piston to rise and fall at least three times. On the down stroke the air was passed out through the valve on the bottom of the motor well. The air was thoroughly agitated by the fan during this flushing process.

Air Supply

It was considered inadvisable to use the laboratory compressor as an air supply because this machine was well lubricated and a certain amount of oil-vapor contamination would be unavoidable. Accordingly, a simple pump was built in which the cylinder and piston were unlubricated. The piston was sealed by a leather cup washer pressed tightly against the cylinder walls by an internal expanding cast-iron split ring. A small quantity of neat's-foot oil was used to soften the leather washer at the outset and a little graphite paste was rubbed on the cylinder walls, then wiped off until they were practically dry. No further lubrication was supplied to the pump throughout the duration of the tests.

The piston-rod guide, which formed the lower cylinder head, was well lubricated with graphite paste, but inasmuch as the pump was single acting and the air was handled entirely above the piston, very little contamination would be expected from this source. The pump was driven by an electric motor.

The dew point of the air was controlled by means of a drying tower (58) and a humidifier (59). (See fig. 2.) The drying tower contained aluminum oxide with which a dew point of about -75° F was obtained. For dew points intermediate between this value and that of atmosphere, a part of the air was by-passed through a flask containing distilled water, and then returned to the line. The air entered the flask through a glass tube which terminated about 2 inches above the surface of the water. A silk wick was fastened to the end of the tube and allowed to hang in the water. All air entering the flask passed through the saturated wick and was thereby well humidified. The exit from the flask was located at the top, well above the surface of the water. The quantity of wet air admitted to the main air stream was regulated by valves (60) and (61). The drying tower and flask were protected from excess pressure by a relief valve (62) inserted in the pump line.

Dust particles were removed from the air by passing it through a filter (63) 18 inches long and 3 inches in diameter, which was packed with glass wool.

After leaving the filter the dew point of the air was determined by drawing out a small sample from the line and allowing it to flow slowly through a dew-point hygrometer (64) which consisted of a polished chrome-plated tube through which cold ether flowed. The ether was cooled by mixing it with solid carbon dioxide. The temperature of the tube was regulated by controlling the rate of flow of cold ether. When frost commenced to form on the surface of the tube, the dew point was read from a toluene thermometer, the bulb of which was immersed in the tube.

Additional remarks on this dew point hygrometer and also on the drying tower will be found in reference 4.

Pressure-Recording System

A strain gage on the cylinder head was used for determining pressures in the combustion cylinder. This unit consisted of a thin strip of insulating material, 1/4-inch square, on which was wound sufficient turns of fine "isoelastic" wire to make the resistance 1000 ohms. The gage ((13), fig. 1) was cemented on the underside of the cylinder head with Bakelite cement. This side of the head was flat and the upper side was concave. There was a minimum thickness of 1/32-inch at the center where the gage was located. When the cylinder head deflected under pressure, the unit was stretched and the electrical resistance of the wire varied in proportion to the strain. This resistance change was directly correlated with change in cylinder pressure by proper calibration. (See appendix C.)

The gage was placed in series with a set of "B" batteries, and a cathode-ray oscillograph was connected across the terminals of the gage. The voltage drop occasioned in the gage by the change in pressure in the cylinder was registered by the deflection of the spot on the cathode-ray tube. The amplitude of this deflection was proportional to the change in cylinder pressure. The reliability of the method is discussed in the section PRECISION OF PRESSURE MEASUREMENTS. The actual circuit used is shown in figure 5, and is described in detail in appendix C.

The camera used for photographing the spot deflection is shown mounted on the table in front of the oscillograph in figure 3. A hood was placed between the oscillograph and the camera to prevent the film from becoming fogged. A close-up view of the camera is shown in figure 6.

This camera consisted of a duralumin case containing the only moving part, a duralumin drum sprocket $1\frac{1}{8}$ inches in diameter. A strip of 35-millimeter film, 2 to 10 feet long, was coiled loosely in the supply box, mounted over the slot at A, and threaded over the drum with 1 or 2 inches projecting into the receiving box mounted over the slot at B. The boxes are not shown in figure 6. The drum was driven through a clutch by a 1/8-horsepower synchronous motor turning 1800 rpm, and the film speed was determined by the selection made in a gear train which may be seen in figure 3. Film speeds ranging from 25 to 400 inches per second could be obtained.

The supply and receiving boxes could be removed and loaded or unloaded in the darkroom without disturbing the camera. The camera clutch was engaged by means of a solenoid ((67), fig. 2) actuated by an adjustable timing switch ((68), fig. 2) which was closed by the falling weight. The instant of closing could be altered by sliding the switch up or down on the weight guide. The low inertia of the drum and film and the ample driving power provided, brought the drum up to speed in a fraction of a revolution. This information was obtained by taking a record of a 60-cycle wave and noting the time required for the wave to become symmetrical.

Provision was made for registering a time reference mark on the film by passing a high-tension current from a spark coil through a small neon lamp. This lamp is shown in figure 6 mounted in a small plastic block. The block fitted in a hole in the back of the camera case and was made detachable so that the hole could be used when focusing the camera. The flash was reduced to a sharp vertical line by an adjustable slit in a rectangular plate (shown in fig. 6 between the case and the plastic block), which was held in contact with the back of the film. The lamp was actuated by a set of breaker points ((69), fig. 2) which were tripped by the falling weight.

In early tests the oscillograph was used in close proximity to the compression machine as shown in figure 3, but with this arrangement the oscillograph records were distorted by the pressure wave which emanated from the cushion ports at the end of the stroke and jarred the instrument. Accordingly, a soundproof box (not shown) was built around the oscillograph and the whole assembly moved about 20 feet from the compression machine. These modifications were helpful but not entirely satisfactory.

Piston-Motion Recording System

A camera, similar to the one described in the preceding section, was used to photograph the motion of the piston. This camera is shown in figure 3, mounted on the steel table with its lens trained on one of the cylinder ports. The lens mounting incorporated a small hood, in which a thick plane lens was placed a short distance ahead of the lens proper in order to protect it from shock and oil mist when the cushion pressure exhausted through the ports. The plane lens could be easily removed for cleaning.

The outer surface of the piston skirt was blackened by a commercial "phosphate" process, and 14 horizontal lines about an inch long and spaced 1/4 inch apart were cut in the surface and filled with white enamel. The lines passed successively in front of the cylinder port as the piston moved downward. The vertical dimension of the port was 3/8 inch so that at least one white line was always in view. Although the phosphate process darkened the surface of the piston sufficiently, it produced small ruts in the ground surface and reduced its gastightness. This was the principal reason why the lead bands were plated on the piston skirt.[1] (See appendix B.)

The white lines were intensely illuminated by two spotlights ((71), fig. 1) each containing a 150-watt projection-lantern bulb. Two lights

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[1]Note that the piston skirt is referred to here and not the piston snout.

were necessary in order to eliminate shadows cast by the shoulders of the port. The lamps were flexibly mounted on the ends of long arms which were supported, independently of the compression machine, by a vertical support ((72), fig. 2) which rested on rubber vibration isolators.

A vertical slit, similar to the one used in the oscillograph camera, was placed in front of, and in contact with, the film on the optical axis of the lens. Thus only a small segment of each white line appeared on the film. As the piston moved downward, the small image of the white-line segment (essentially a point) moved vertically across the film at the same time the film moved horizontally. The resulting trace on the film was an oblique line the slope of which gave the velocity of the piston. A series of these sloping lines was obtained as the multiple lines in the skirt passed the port. (See fig. 7, lower record of the pair numbered 198.) Since the location and spacing of the lines on the piston were known, the position of the piston at any instant could be accurately determined. In this manner it was easy to detect whether or not the piston bounced at the end of its stroke.

A reference mark was impressed on the film by a neon flash bulb, as previously described for the oscillograph camera, and the same circuit and breaker points were used so that a simultaneous flash occurred in both cameras. The reference marks thus established an instant of time common to both events.

The piston camera was also started by means of a solenoid ((73), fig. 2) and an adjustable switch ((74), fig. 2) mounted on the weight guide.

When adjusting the cushion pressure, a certain amount of leakage occurred past the piston skirt into the space above. This back pressure sometimes resulted in a slight premature motion of the piston and was undesirable not only because it changed the effective stroke and thus the compression ratio, but also because it deranged the relation between driving and cushion pressures to the extent that the piston seated with a severe mechanical shock. For the purpose of indicating any such motion a small contact was arranged in a plastic block, which was pressed into one of the ports in the main cylinder ((32), fig. 1). The block contained a finger which extended through the port and pressed against the side of piston. Any slight motion of the piston moved the finger and broke the contact, thereby extinguishing a small lamp ((75), fig. 2) on the control board. In order further to prevent any build-up of back pressure, a small hole about 1/64 inch in diameter was drilled through the cylinder wall ((76), fig. 1) into the space above the piston. This hole was not large enough to affect materially the driving pressure immediately after the release of the poppet valve.

PRECISION OF PRESSURE MEASUREMENTS

Differences between values of pressure measured from the records and true values may be ascribed to the following causes:

(1) Leakage from the combustion chamber

(2) Decay in oscillograph response with time

(3) Heat transfer from the hot gases to the colder cylinder walls

(4) Variations in the strain-gage output with use

(5) Nonlinearity of the cathode-ray oscillograph response

(6) Nonlinearity of the optical system

Tests were therefore made to determine the magnitude of each of these effects.

(1) Determination of Leakage

Leakage from the combustion chamber under static conditions was determined in the following manner:

A nitrogen cylinder and pressure gage were connected to the combustion chamber by means of a special cylinder head identical with the regular head but having a threaded hole in the center. Suitable precautions were taken to have all connections gastight so that all leakage would be confined to the combustion chamber. The chamber was then filled with nitrogen at 800 pounds per square inch. The nitrogen cylinder was then shut off and the fall in pressure timed with a stop watch. The piston was kept at the bottom of the cylinder during these tests because it was in this position (i.e., after compression) that the maximum pressures were encountered. The jacket temperature was raised to a value approximately the same as that used when the machine was in actual use in order to reproduce any difference of expansion between cylinder and piston.

The results of the leakage test are shown in figure 8. The upper curve shows the observed rate of leakage immediately after plating a new lead band on the piston snout. The middle curve shows the observed rate of leakage after the apparatus had been used to make 50 runs. It will be noted from this curve that the seal loses some of its effectiveness with usage. The lowest curve represents, very nearly, the actual leakage from the chamber. This last curve was obtained from the middle curve by adjusting the points to allow for the volume of the connecting lines and fittings. Starting from a given initial pressure, the time required for the pressure to drop through a given range is directly porportional to the volume of the combustion chamber, and since the chamber was small, the volume of the connecting lines and fittings had to be taken into account. The method of making this adjustment is given in appendix D.

The maximum pressure attained at the end of the stroke for the highest value of compression ratio used was 518 pounds per square inch. From the lower curve of figure 8 it will be seen that the rate of pressure drop at this pressure is 30 pounds per square inch per second, but the duration of the delay period in these high-compression runs occupied only about 0.005 second; therefore the fall in pressure due to leakage during this interval would be about 0.15 pound per square inch, or less than 0.04 percent. At the other extreme where a delay period 11 inches long (0.055 sec) was obtained at a compression pressure of 380 pounds per square inch, the rate of pressure drop is, from figure 8, 10 pounds per square inch per second. Hence, the total drop in pressure during the delay period would be 0.55 pound per square inch or 0.15 percent.

This test was repeated periodically and the piston removed and replated with lead when necessary. This was done, on the average, about every 80 runs.

(2) Decay in Oscillograph Response

If a direct-current voltage is suddenly applied across the input terminals of a cathode-ray oscillograph and then maintained constant, the amplitude of the spot deflection will at first represent the true value of the applied voltage, but as time goes on the amplitude will slowly drop to zero. This effect is a characteristic of the amplifiers. The pressure-time records in this case represent just such an electrical phenomenon and it was important to know how much of the drop in the trace during the delay period was due to this electrical decay.

This was ascertained by suddenly impressing a direct-current voltage on the oscillograph by means of a suitable circuit and taking a record of the response at the same film speed (200 in. per sec) as used in the investigation reported in reference 1. The voltage used gave about the same spot deflection as that resulting from the compression of the charge. The drop in amplitude, 0.05 second (10 film inches) after the sudden application of the voltage, was smaller than the errors involved in measuring.

(3) Heat Transfer from Hot Gases to Cylinder Walls

The extent of the heat losses after compression was appraised by making a run in the usual manner except that the combustion cylinder was filled with air in order to prevent an explosion. The pressure record was made very long so that the effect, even if small, could be easily recognized.

Measurements showed that the fall in pressure with time was 8.7 percent for the first 10 inches after the compression and continued to drop linearly for an additional 30 inches (see fig. 9). In a comparison of these results with the preceding tests on leakage and decay, it is apparent that cooling is the most troublesome source of loss of pressure during the delay.

This test does not show how much heat was lost during compression, but it may be used to form a good estimate by comparing the surface-volume ratios in the cylinder at the beginning and end of the stroke. The comparison shows that the ratio is 30.9 times greater after compression. Thus the record obtained for test (3) shows the extent of heat transfer under the worst possible conditions. Assuming, however, that the heat loss during compression is equally as great, the departure from the true adiabatic pressure (for a compression time of 0.006 sec) would be no greater than 1 percent.

Leakage during compression was not measured, but there is no good reason to believe that this would be as great as that determined under static conditions unless the bore of the cylinder were tapered. The cylinder walls were parallel within 0.0002 inch.

From the results of test (3) it may be safely assumed that the pressure rise during compression was at least 99 percent of the true adiabatic pressure rise.

An interesting experiment along these lines, which further demonstrates how the efficiency of the compression process is improved by reducing the compression time, was made by Tizard and Pye (reference 5). They used a rapid compression machine in which the piston was actuated by a crank and connecting rod (see appendix A). Their data for air are shown plotted in figure 10. It will be readily seen how the ideal adiabatic pressure (no heat loss) is approached as the compression time decreases. This curve cannot be directly applied to the present apparatus in which the cylinder shape and dimensions were different, the maximum compression pressure was about twice as great, and the cylinder walls were not lubricated, as in Tizard and Pye's apparatus. All these considerations with the exception of cylinder shape would make the heat losses less in Tizard and Pye's apparatus for the same compression time, but it will be noticed that their smallest compression time was eight times longer than that used in the present work (0.05 sec compared with 0.006 sec), and from figure 10 it may be computed that the pressure rise associated with a 0.05 compression time would be 96.5 percent of the adiabatic pressure rise. For mechanical reasons, however, their routine compression time was limited to 0.14 second and thus their working compression pressure was only 90 percent of the adiabatic.

(4) Variation in Strain-Gage Response

A curve showing the response of the strain gage against applied pressure is given in figure 11. This curve was determined at the conclusion of the work by the method described in appendix C. The curve shows that the response is linear up to 800 pounds per square inch and then departs slowly from a straight line so that at 1800 pounds per square inch it is about 15 percent low.

This deviation could be allowed for if the sensitivity of the gage remained constant, but unfortunately this factor varied with use. The sensitivity decreased after a few runs - in one of which the piston seated so severely that it was thought the mechanical shock had loosened the gage somewhat - however at a later period during the work the sensitivity increased again. Exact measurements of explosion pressures therefore could not be obtained. The peculiar behavior of the strain gage was probably due to the difficulty of satisfactorily securing the unit to the cylinder head.

Compression pressures, however, may be safely taken at their adiabatic values.

(5) and (6) Nonlinearity of Cathode-Ray Oscillograph and Optical System

Over-all errors in pressure due to nonlinearity of the cathode-ray oscillograph and optical system were checked by means of the same circuit used in test (2). But in this case, various voltages covering the useful range of spot deflection were suddenly applied across the oscillograph terminals and a separate record made for each deflection.

Values of spot deflection measured on the films against applied voltage are shown in figure 12. The curve is linear within the precision of measurement. The oscillograph-camera system, then, has no significant errors.

These records also gave a means of determining the decay (as in test (2)) for values of spot deflection greater than the compression-pressure range. For deflections in the explosion-pressure range the decay amounted to about 2 percent after 10 inches of "delay."

INTERPRETATION OF RECORDS

Records of piston displacement against time and cylinder pressure against time, taken at a film speed of 200 inches per second, are shown in figure 7. Time increases from left to right and vertical distances on the original piston-displacement records are 0.80 times actual size.

Record 181 shows that the driving and cushion pressures were not properly adjusted. The cushion pressure was too low, for the piston hit bottom sharply at A, rebounded a vertical distance of 0.07 inch, and came to rest at B. In record 123 the cushion pressure was too high. The piston descended to within 0.19 inch from the bottom at C, and although the ports were partly open at this point, the release of pressure was not rapid enough and the piston surged up an additional 0.09 inch at D. Here the cushion pressure dropped sufficiently to allow the piston to move downward again thus completing the stroke at E. The seating was not accomplished smoothly as can be seen from the slight mechanical bounce just beyond E.

When the driving and cushion pressures were in proper adjustment a record like the lower one in the pair numbered 198 was obtained. The small fillet with the slope tapering off to zero an instant before the end of the stroke, at F, shows that the velocity was reduced to zero just before the piston seated. Thus there is neither surge nor bounce and the record may be taken as an ideal for piston motion. The compression time for this record is 0.0058 second. A slight wavering of the lowest line can be observed after seating but this does not represent a piston vibration. It is due to the shaking of the camera lens after the impact. This was demonstrated by loosening the lens mount whereupon the amplitude of the vibration was greatly increased. An additional check was to be had in the trace made by light reflected from the lower edge of the port in the cylinder sleeve. This trace did not appear in all the records, but can be seen rather faintly in record 181 as the lowest white line in the group. The undulations in this line, beyond B, parallel those of the piston and thus indicate that there was no relative motion between the piston and the cylinder sleeve or, in other words, the piston remained tightly seated.

The records shown in figure 7 show 12 sloping lines. The first of these lines is designated in record 181 by the letter "G" and the last by the letter "H." The bright white band at the beginning of the records, just below the first white line, is due to light reflected from the upper part of the lead band, which made a good reflecting surface. Although 14 horizontal lines were inscribed on the piston skirt only 12 lines show in all these records because the lowest 2 lines were always below the port aperture in the sleeve.

On most of the records the last line appears double because of an image of the lower edge of the piston port being formed just above the line. It is more or less visible, depending on lighting conditions. It may also be noticed that before the piston starts to move, the field is somewhat fogged because of undesirable reflections from the piston skirt, but after the piston has seated the field is clear, showing that the ports are open. If too much lubrication is placed on the piston skirt, a white smoke, or mist, appears in the nitrogen which is exhausted through the ports, and this obscures the final phase of the motion; therefore precautions were taken to keep the lubrication at a minimum. It should be recalled that the piston skirt ((23), fig. 1) was lightly lubricated, but not the piston snout ((9), fig. 1), and thus the combustion chamber was always kept dry.

The pressure record for run 198 (fig. 7) is shown directly above the piston record for this run. On the vertical pressure scale, 1 inch represents approximately 2700 pounds per square inch (in this particular record). The record was taken at the same film speed (200 in. per sec) as the piston record, and they are so alined that a vertical line drawn across them represents an instant of time common to both. This synchronization of the records was first accomplished by means of the neon flash bulbs described previously, but after it was noticed that the instant of seating of the piston was always accompanied by a high-frequency vibration on the pressure record, it then became unnecessary to use the flash timers.

In the pressure record for run 198 a small amplitude vibration, probably caused by the mechanical shock of the weight hitting the poppet-valve stem, can be seen at I. Just beyond this disturbance, at J, a small vibration of higher amplitude can be seen which may be due to the poppet valve impinging on the top of the piston. However, no marks have been found on the top of the piston nor bottom of the valve to indicate with any certainty that such is the case. Between I and J the piston starts to move and the pressure line slopes upward as the cylinder pressure increases. Maximum compression pressure occurs at K, as the piston reaches the end of the stroke, and the instant of impact is recorded as a sequence of high-frequency vibrations. This is the disturbance which serves as the reference mark for alining the two records. This disturbance was usually more pronounced than that shown in record 198, but in any case it did not represent a severe mechanical shock because very little impression was left on the impact rings ((19), fig. 1), in the course of normal operation.

The compression ratio for run 198 was 11.7:1 and, assuming adiabatic compression with an exponent of 1.32, the pressure at K is 379 pounds per square inch. The pressure then drops off slightly, presumably because of cooling, and reaches a minimum at L. Beyond L the heat generated by the preliminary reactions offsets the cooling and the pressure rises again, gradually at first and then rapidly as the explosion point, M, is approached. It will be observed that, in this particular case, there is no discontinuity in the trace in the explosion region; the curve is characterized by well-rounded fillets just before and just after the explosion. It will also be noticed that there are no high-frequency vibrations following the explosion. This fact may indicate that there were no pressure gradients in the chamber; that is, ignition occurred homogeneously throughout the mixture.

Peak pressure for run 198 occurs at N. The height of point N above the line of zero pressure is 0.39 inch which is 2.79 times the height of the maximum compression pressure. Since the compression pressure was 379 pounds per square inch, the peak pressure should be $379 \times 2.79 = 1055$ pounds per square inch. Actually this pressure is about 15 percent below that calculated theoretically from thermodynamic charts (reference 6). The reading is low most likely because of the nonlinear response of the strain gage. The curve falls off gently after peak pressure because of heat losses, dissociation, and leakage. The piston record shows that the piston remained tightly seated during and after the explosion.

The pressure curve is smooth as far as the region of point O, after which it gradually breaks into a series of irregular waves the amplitude of which increases with time. These waves do not represent changes in the pressure level. They are the result of microphonic excitations in the oscillograph amplifiers caused by sound waves set in motion by the opening of the cushion-chamber ports at the end of the stroke. This difficulty was eliminated toward the conclusion of the work by changing oscillographs. (The extra oscillograph was not available at the outset.) On the whole these extraneous waves did no great harm except when the delay was long, for then the trace was badly distorted in the explosion region.

The explosion curve shown in record 198 is not characteristic of all records; it represents a mean between two extreme types. In one extreme type the combustion took place suddenly at the end of the delay period and represented a discontinuity in the trace. This type is exemplified by record 188. The rise in pressure due to the preliminary reactions becomes noticeable near the middle of the delay period and continues until the general pressure level has risen by approximately 30 percent. An abrupt change then takes place and the pressure attains its maximum value "instantaneously." The time required for this "instantaneous" change can be estimated from the record at less than 0.00005 second. This type of explosion is always followed by high-frequency oscillations which may represent either gas vibrations in the cylinder or mechanical vibrations of the cylinder head at its natural frequency, or both.

If the oscillations represent gas vibrations then it would follow that ignition of the charge did not take place at exactly the same time at all points, or that the rate of burning varied in different parts of the charge. Only through one or both of these effects could pressure gradients, and thus pressure waves, or gas vibrations, be set up. In this case a slower rise of pressure than that indicated by record 188 would be expected. On the other hand, if the charge ignited simultaneously and burned at the same rate at a sufficiently large number of points, there would be no large pressure gradients, even though the rate of pressure rise was extremely rapid, and the gas as a whole would remain quiescent. The suddenness of the reaction, however, might act on the cylinder head like a hammer blow and cause it to oscillate at its natural frequency. This explanation seems more plausible since it will be noticed that the vibrations following the explosion appear to be of the same frequency as the vibrations following the mechanical shock of impact after compression. The mechanical vibrations are small in record 188, but a good comparison can be had from record 287, also shown in figure 7. The frequency of the mechanical vibration should be the same in all records, and this appears to be the case.

A general survey of the type of explosion exemplified by record 188 shows that the time required for the post-explosion vibrations to damp out is about the same as that required for the mechanical vibrations caused by piston impact to damp out, when the initial amplitude is the same in both cases. This would further indicate that all the observed vibrations were purely mechanical in nature.

The other extreme type of explosion record is characterized by record 287 (fig. 7). Here the pressure rises continuously from the end of compression until the maximum pressure has been attained. The slowness of this pressure rise can be explained either by the theory that the combustion proceeds by means of a progressive burning, that is, a small initial inflammation which is propagated by means of a flame front, or by the supposition that combustion proceeds by means of a series of chain reactions without any marked acceleration, that is, as though the "preliminary reactions" proceeded to completion at a more or less uniform rate. Good reasons can be advanced in support of either process, but the matter can be definitely settled only by extended experimental methods. A transparent window in the combustion chamber through which the ignition and flame development could be photographed would be helpful in this respect.

The facts that the records are not all of the same type and that some pressure rise always occurs before explosion introduce difficulty in defining the delay. For cases in which the explosion is sudden, the delay is easily defined as the interval between the end of compression and the instant of explosion. In other cases, such as that exemplified by record 287 in which the pressure rises continuously after compression without any discontinuity, a definition of delay must be more or less arbitrary. Delay can be defined in several ways and a few definitions have been given in reference 7. For work with the rapid compression machine, delay will be defined as the time interval in seconds between the end of adiabatic compression and the instant at which peak pressure is attained.

CONCLUSIONS

A rapid adiabatic compression machine has been developed at the Massachusetts Institute of Technology with the following characteristics:

1. The machine gives a compression time of less than 0.006 second or about one-eighth that of any previous machine.

2. By raising the driving pressure above the value used in the present tests (500 lb/sq in.) the compression time can be substantially reduced.

3. The machine incorporates an accurate and satisfactory method of recording piston motion.

4. The electrical pressure-recording system is entirely satisfactory for the measurement of delay periods, but is unreliable for the accurate determination of pressures.

5. The absence of lubricant in the working cylinder constitutes an advantage over previous machines and eliminates a serious source of error in the measurement of ignition delay.

6. Because tests can be conducted with a few cubic centimeters of fuel the apparatus is suitable for determining the combustion characteristics of pure compounds available only in small quantities.

Sloan Laboratories for Aircraft and Automotive Engines
Massachusetts Institute of Technology
Cambridge, Mass., December 29, 1944

APPENDIX A

REVIEW OF PREVIOUS COMPRESSION-IGNITION MACHINES

A study of the ignition temperatures of gases by means of a rapid adiabatic compression was first undertaken by Falk (reference 8) in 1906 at the suggestion of Nernst. Falk described his apparatus as follows:

"In order to heat the gas whose ignition temperature was to be determined, it was necessary to enclose it in a small vessel supplied with a device for allowing the gas to be compressed instantaneously. Two pieces of apparatus were constructed on the same plan, but of different sizes. A section vertically through the center is shown in figure [13]. A steel cylinder AA was screwed into a wrought iron plate, LL, so as to fit absolutely air-tight. The piston head B fitted closely into the cylinder AA. The piston rod CC was made a little narrower (about 2 mm) than B. The piston head together with the piston rod was made of one piece of steel. It was topped by an iron plate, D, screwed on to the piston rod. In order to have the piston head slide into the cylinder and at the same time permit no leakage, three circular grooves each 1 mm wide and 1 mm deep were cut into the former and wound with hemp. The cylinder was filled with the gas to be studied through E, a brass tube 5 mm in diameter soldered to the cylinder. The compression was obtained after enclosing the gas in the cylinder and pushing the piston down below the opening E so as to shut off access to the air by allowing a weight to fall on the plate D. By increasing the size of the weight and the distance of its fall, as great a compression, and consequently as high a temperature as was desired, could be obtained. A brass ring, 1 cm in width, was fitted on the piston rod so that it could be moved up and down only by the use of some force. This served to show the smallest volume of gas in the cylinder during a compression, as the ring was pushed up by the walls of the cylinder as the piston descended, and then remained fixed in position when the piston moved upward again, thus indicating the lowest point reached by the piston. Knowing the dimensions of the apparatus, the volume reached by the compression could then be calculated. Lanoline was found to be the best lubricant for the piston, and was used throughout this work."

Falk improved his apparatus slightly in 1907 when he substituted a ring of fiber board clamped to the piston rod by means of a screw, instead of the brass ring, and substituted two leather packed grooves on the piston for the three hemp-wound grooves. (See reference 9.) A photograph of this machine is shown in figure 14. Falk constructed a total of four compression machines with inside cylinder diameters varying from about 1 inch to 2 inches and concluded:

> That there is no radiation or loss of heat in any other way during compression . . . because the four pieces of apparatus differing so much in size give essentially the same results.

The machine Falk constructed did not provide for the direct measurement of cylinder pressures and because of this deficiency his machine gave no evidence of the phenomenon of ignition delay. The apparatus was used only for obtaining data from which the ignition temperature of a gas could be computed. The ignition temperature computed by Falk would be that temperature at which the apparent delay is zero. (See reference 7.)

The method of adiabatic compression was next investigated in 1914 by Dixon, Bradshaw, and Campbell (reference 10), who gave the following description of their apparatus (fig. 15):

"In order to study the initiation of the flame produced by the adiabatic compression of gases, experiments were made in glass tubes so arranged that the flame could be analysed by being photographed on a rapidly moving film.

"In figure [15], AA was a stout glass tube 12 mm in diameter and 650 mm long containing the gases to be compressed. This tube was held by means of wooden clamps in a horizontal position with its closed end (cushioned by a pad of velvet) against a stout wooden support. The steel piston-rod BB could be rapidly forced into the tube by the falling pendulum (W), which was suspended from a beam in the ceiling by a trellis-work 3 metres long [fig. 16].

"To prevent the piston-rod from buckling under the sudden strain, it was held by three steel cases (C, D, E) which slid one inside the other as in a telescope, and supported the long piston as it was being pushed home.

"The pendulum could be arrested at any desired point by means of the wooden blocks (HH), the position of which could be adjusted by inserting or removing steel plates (FF) - thus allowing a smaller or greater compression.

"The image of the flame was focused by means of a lens on to the photographic film, which was fastened on to a wheel, 1 metre in circumference, capable of being rotated in a vertical plane at any speed between 20 and 60 revolutions per second as desired. The actual motion recorded on the film is therefore compounded of two velocities: (1) the vertical downward velocity of the film, and (2) the horizontal velocity of the image of the flame."

The principal improvements in this apparatus over Falk's was that the piston was stopped at a more definite point in the stroke, and records of the explosion were obtained. By means of these records Dixon and his associates were able to show that Falk's machine gave erroneous results. They said:

> It was evident from these experiments [i.e., records] that the piston was not stopped at the moment the gases reached their ignition point, but at the moment the moving force was removed. The position of the collar showed that the momentum of the piston alone was not sufficient to move it appreciably after the arrest of the pendulum . . . . . <u>The minimum volume observed when a gaseous mixture is fired by adiabatic compression is therefore no criterion of its ignition point</u>.

Also, regarding a statement of Falk that a compression wave, due to the motion of the piston, might affect the ignition temperature, Dixon and co-workers said:

> In the experiments so far made we could detect little evidence of any violent compression waves.

It appears that Dixon and co-workers were the first to recognize clearly the existence of an ignition delay, for they remarked:

"Some idea also may be formed from these experiments as to the time which elapsed between the moment when the 'ignition-point' was reached and the moment when the flame started. If we assume that the ignition-point was just reached in the second experiment when the temperature was about 578°(C), and the piston was 36 mm from the closed end of the tube, we may also assume that the ignition-point was reached in the fifth experiment when the piston arrived at the same place in its forward movement. The photograph shows, however, that in the fifth experiment the piston had time to travel forward at least 22 mm from this position before the flame appeared. The time required for the piston to travel this distance was at least 7 mille-seconds. The heat produced by the compression from 36 to 14 mm would have raised the temperature of the gases from 578°(C) to 975°(C) (approximately), and this rise of temperature would have hastened the self-heating. A pre-flame period of 7 mille-seconds is therefore a <u>minimum</u> for this mixture when brought to the 'ignition-point.' On the other hand, by making the pendulum break an electric circuit just when the piston was stopped 36 mm from the end of the tube, it was possible to photograph a spark on the moving film, and so to measure the time-interval between the spark and the first appearance of the flame. This gives the pre-flame period about 13 mille-seconds when the retardation of the spark is taken into account. The pre-flame period is therefore of the order of 10 mille-seconds (or 1/100th of a second) for this mixture under the conditions of the experiment."

What Dixon and co-workers called the "pre-flame period" is now generally referred to in engine work as the "delay period," or more simply, the "delay." The variation in the delay period with manner of compression, as noted by Dixon and colleagues, is of fundamental importance in the theory of engine detonation. (See reference 7.)

Falk's work was repeated by Dixon and Crofts (reference 11) with a new apparatus. Experience gained in the preliminary work with the glass ignition chamber showed:

. . . what modifications of Falk's apparatus would be desirable in order to determine the ignition-point of gases by adiabatic compression. The cylinder must be sufficiently wide to prevent appreciable cooling by the walls of the central mass of gas during compression; it must be sufficiently long to give a 'final volume' that can be measured with accuracy; the piston must be driven in rapidly, it must work gas-tight without the lubricant coming into contact with the explosive mixture, and it must be stopped the moment it has compressed the gas to the true ignition-point. After many experiments an apparatus was constructed that fairly met the above requirements.

The apparatus of Dixon and Crofts is shown in figure 17 and is described in their paper as follows:

"A steel cylinder 56 cm long and 11 cm in diameter was bored with a central cavity (C) . . . 30.2 mm in diameter to a point 45 cm from the upper end; the cavity was continued through the cylinder in order to facilitate the boring, but this lower part was enlarged, and could be closed by a steel plate (Pt) kept in place by means of powerful screw (S). The joint was made gas-tight by means of an annular washer (W) of lead, which was squeezed well into place by help of the screw. Through the side-wall a hole was pierced at the bottom of the cavity, just above the steel plate, and the hole was fitted with a steel plunger (Pl), by means of which the cavity could be shut off during an experiment; when open, however, connexion could be made by means of the three-way glass tap (T_1) (not shown) with the gas-holder (and manometer) or with the outside air.

"A cylindrical steel piston (Ps) with a head (H) 5 cm long and 5 cm in diameter fitted loosely into the explosion chamber. At its inner extremity it was furnished with a leather washer (L), and beyond this with a bronze cap (B), which made a close sliding fit with the cylinder walls.

"To prevent damage to the walls it was necessary to have the piston a loose fit in the cylinder, but in its descent it was centred by means of the steel collar (Col), which was fastened down by means of four screws. Hard chrome-steel plates (P) cut with a slot could be placed on this collar, and served to stop the piston by catching the piston-head at any desired point in its descent; these plates were made of various thicknesses 2 and 1 cm, 2, 1, 0.2, and 0.1 mm - and were calibrated from time to time.

"The cylinder was held by an iron frame (F), which rested on a large bed of concrete; it was surrounded by a brass water-jacket (J) (not shown) fitted with a stirring arrangement.

"The compression was effected by allowing an iron weight . . . of 76 kilos. ($2\frac{1}{2}$ cwts) to fall from a height (usually of 1.5 metres (5 ft)) on to the piston-head -- the weight falling within three iron guides . . ."

Although this apparatus embodied many improvements, it suffered from two serious defects, namely, that the piston was free to bounce after completing its stroke, and no records of cylinder pressure were provided. Under these circumstances, determinations of ignition temperatures were ambiguous, and accurate measurements of delay impossible. Dixon and Crofts mention, however, that they later equipped their machine with a device which gave a record of piston motion (from which they ascertained that the compression time was 0.06 sec), but they did not publish this record.

A compression machine free from the defect of rebound was built by Cassel in Germany in 1916 (reference 12). Cassel pointed out that adiabatic cooling of the mixture would take place if the piston were allowed to rebound at the end of compression and that this cooling might be sufficient to snuff out an incipient explosion. Cassel also provided an indicating mechanism which gave a record of piston motion. A sketch of Cassel's apparatus is shown in figure 18.

This apparatus consisted of a heavy steel cylinder A, 1.74-inch inside diameter, with a threaded opening B, 6.89 inches from the bottom, for admission of the mixture. The piston C carried two leather rings lubricated with paraffin oil. The piston head D was guided by stout steel uprights E (only one is shown in fig. 18), screwed into the base of the machine. The piston head carried a rod at the end of which a stylus F was fixed. The stylus pressed against a drum G which rotated concentric with the combustion cylinder on the ball bearings H. The drum was coated with lampblack, and was rotated at constant speed by an electric motor with a heavy iron flywheel. As the piston moved, the stylus scratched a record of the motion on the rotating drum. In order to prevent the piston from bouncing at the end of compression, a set of brake shoes was provided on the guide which held the falling weight in position. A set of lead washers was also placed on the top of the cylinder to dissipate the energy at impact. This equipment is not shown in the sketch.

A record taken by Cassel is shown in figure 19. That he succeeded in eliminating the bounce is apparent. The line AB represents the descent of the piston with the impact occurring at B. There is no evidence of bounce in the region BC. At C the explosion occurred forcing the piston upward rapidly until the piston head was brought to rest by the springs I (fig. 18). The wavy lines in figure 19 are timing marks, generated by a tuning fork making 435 vibrations per second, and indicate that the compression time was about 0.04 second. The record of figure 19 was obtained by checking the descent of the piston at gradually decreasing distances from the bottom (and thus gradually increasing the final pressure) until ignition was just realized, and therefore the time interval BC gives the maximum delay. Cassel plotted a curve (fig. 20), based on computed pressures, in which he termed the delay period the "reaction period." Thus Cassel, too, clearly recognized the existence of the ignition delay.

Dixon later (about 1922) improved his apparatus to prevent the piston from bouncing by a method similar to Cassel's. Dixon placed a lead collar on the upper end of the cylinder to receive the impact of the piston rod and provided strong spring-actuated clamps which seized the rod and held it firmly at the completion of compression.

The next piece of compression-ignition equipment was designed and built by H. R. Ricardo and used by Tizard in his investigations of engine detonation (reference 13). The apparatus was later used by Tizard and Pye (reference 14) in furtherance of the work and is described by them as follows (see fig. 21):

"Figure [21] shows diagrammatically the arrangement of the mechanism. A very heavy flywheel A rotates quite freely on the shaft B, and is kept spinning by an electric motor at about 360 R.P.M. The shaft B carried between bearings the crank D, and outside one bearing, the internal expanding clutch C, which can engage with the flywheel rim.

"The piston E moves vertically in the jacketed cylinder F, which has an internal diameter of $4\frac{1}{2}$ inches and can be raised or lowered bodily in the heavy cast-iron casing of the apparatus when the compression ratio is to be altered. The length of stroke of the piston is 8 inches, and its motion is controlled by the two hinged rods G and H of which the latter is carried on a fixed bearing at K. The hinge L is linked up with the crank pin by the compound connecting rod N. That part of the connecting rod attached to the crank pin is tubular and contains the sliding rod M attached to the hinge L. A clip O carried on the sleeve can engage with a collar on the inner rod and hold the latter rigid in the tube. With the connecting rod locked as one link, the crank is rotated by hand for setting the piston in its lowest position. When a compression has to be made, the clutch is suddenly expanded by a hand lever while the flywheel is running at high speed, clutch and crank are carried round with the flywheel, and the toggle joint ELK is straightened until the hinge L lies on the vertical line between the piston centre and hinge K. At the moment when L is vertically over K it comes up against a leather pad, and a clip comes into action which holds it in this position. At the same moment, too, the clip O releases the two parts of the compound connecting rod, so that while the two rods G and H are held in the vertical position to take the large downward thrust of the piston when explosion of the compressed mixture occurs, the crank, clutch, and flywheel are free to go on rotating, and the shock due to destruction of the momentum of the moving parts is reduced to a minimum. The initial temperature of the gases in the cylinder can be varied by means of a water jacket round the cylinder, and the variation of pressure during and after compression is recorded by means of an optical pressure indicator of the Hopkinson type."

Provision was also made for inserting an electrically driven fan through the cylinder head into the combustion chamber in order to study the effect of turbulence on ignition temperature.

This compression machine was the first to provide direct measurements of cylinder pressures. This feature enabled Tizard and Pye to give an elaborate and convincing demonstration of the ignition delay with the result that new interest and speculation were provoked in the realm of engine detonation.

The apparatus had its limitations, however, and left much to be desired. Some of the shortcomings of the machine and the changes which were later made (1926) to overcome them were summed up by these authors (reference 5) as follows:

"For this purpose a modified apparatus was designed and built, which has the advantage that it can be used for experiments with simple gases, such as hydrogen, which have fairly high ignition temperatures in the presence of air or oxygen. If the initial temperature of the gas before compression is low, high compression temperatures can only be reached by employing high degrees of compression. Thus Dixon and Crofts showed that a mixture of hydrogen and air initially at room temperature had to be compressed in the ratio of 15:1 before ignition occurred. The excessive compression pressures so produced caused considerable experimental difficulties when the compression cylinder is large. To avoid these difficulties, the initial temperature of the gas must be high. In our old apparatus it was impossible to heat the gases initially to a temperature much above 60°(C), since higher temperatures destroy the cup-leathers on the piston, which contain the oil seal necessary to keep the cylinder gastight. In our new apparatus this was overcome by arranging two cylinders in tandem. The upper cylinder contains a plain closely-fitting plunger, and it can be heated to 150-180°(C) by an oil jacket. The lower cylinder is always kept at room temperature, and its piston is fitted with the double cup-leather and oil seal described in the earlier paper. On compression, the pressures in the lower and upper cylinders balance, so that there is no tendency for the gas in the upper working cylinder to escape. The general arrangement is shown in the diagram . . . [See fig. 22]. The indicator of the Collins type, used to record the changes of pressure of the gas, was described in detail by Pye. [Jour. of Sci. Inst., March 1925.]

. . . . .

"The working cylinder has a diameter of 3 inches, and the stroke of the piston is 8 inches. The machine can be arranged to compress in a ratio of either 6:1 or 9:1. But for the cylinder construction the apparatus is practically the same as the previous apparatus.

. . . . .

"It is difficult, however, with an apparatus of this type to compress the gases very suddenly, owing to the inertia of the moving parts. We found that it was necessary for the time of compression to be greater than 0.05 second to avoid fracture of the moving parts; indeed, fracture occurred on one occasion when the time was as short as this, so that as a rule the time of compression was kept constant at 0.14 second.

"Under these conditions the maximum pressure reached by compression is always considerably lower than that calculated on the assumption that compression is adiabatic."

This statement was contrary to Falk's observation that the heat losses in his apparatus were negligible, and to prove their point Tizard and Pye made a series of compressions with air only in the cylinder and another series with hydrogen only. The final pressures were plotted against compression time as shown in figure 10. One unit on the pressure scale equals 0.275 atmosphere. The true adiabatic compression pressure (assuming 1.408 for the adiabatic exponent) corresponds to zero time of compression. Tizard and Pye showed that leakage in the cylinder and increase in average specific heat due to water or oil vapors were negligible in these tests, and concluded that the difference is almost entirely due to heat losses.

In any compression machine, therefore, the precision of results will vary inversely with the compression time. Of all the machines described so far, Cassel's machine shows up best in this respect, with a compression time of 0.043 second (fig. 19). This value corresponds to a rotational speed of 698 rpm, that is, assuming the piston motion to be obtained by means of a crank and connecting rod.

In 1925 another compression machine, similar to Dixon's more recent apparatus, was built in France by Pignot. This machine is described in a paper by M. Aubert (reference 15). The machine possessed certain original details, among which were the method of adjusting the length of the stroke by screwing the plug E (see fig. 23) up or down the threaded piston rod B, the manner of regulating the initial temperature of the mixture by means of the heating coil K surrounding the combustion cylinder, and the use of a thermocouple L, inserted directly in the combustion cylinder, to measure the initial mixture temperature. In order to cope with piston rebound, a set of spring-actuated clamps were devised (see fig. 24) which snapped into the groove H on the plug E (fig. 23) at the end of compression. Pignot did not provide any means of recording cylinder pressures or piston motion in this apparatus, but later modified it to overcome the former deficiency (reference 16) by adding an optical pressure indicator. The pressure-time records published by Pignot indicate that although the compression-time was reduced to about 0.025 second, the piston was not actually prevented from bouncing at the end of the stroke (see fig. 25).

After a lapse of some years, the apparatus of Tizard and Pye was again put into service, this time at the National Physical Laboratory in England by Fenning and Cotton (reference 17), who concluded an exhaustive series of experiments on ignition temperatures in 1929. The results obtained, however, were inconclusive because of the erratic behavior of the machine. Reproducible results were difficult to realize, partly because of, according to these experimenters, surface action, fine particles in suspension in the cylinders, and friction. In an attempt to reduce these effects Fenning and Cotton made an interesting addition to the machine. (See fig. 26.) The upper cylinder was removed and replaced by a mild steel plate to which was clamped a rubber bulb.

The explosive mixture was admitted to the bulb only, and the remainder of the cylinder, which was now well lubricated, was filled with air. Records of pressure changes in the air only were taken.

Although this device looked promising, it did not provide the much desired consistency. In addition, "when used with benzene, hexane, acetone, and ether, the absorption of the vapour by the rubber was so rapid as to exclude the possibility of carrying out any reliable bulb experiments." (See reference 17.)

A decrease in the compression time was the main endeavor of a compression machine developed by V. C. Smith at the Massachusetts Institute of Technology in 1930 under the supervision of H. C. Hottel. (See reference 18.)

Smith used compressed air as the driving force rather than a falling weight or rotating flywheel, but encountered great mechanical difficulties as the speed of compression was increased. His apparatus (fig. 27) consisted of a combustion cylinder A, 2-inch inside diameter, machined from a steel ingot, and an upper cylinder B, 3-inch inside diameter, machined from seamless steel tubing, the cylinders being fitted together in a manner which allowed them to be readily separated after a test. The lower cylinder was stepped into a heavy cast-iron base C, which was bolted to a concrete pedestal. The mixture was admitted by means of a valve D and direct pressure measurements were made by means of an optical indicator set in the cylinder head E. The piston consisted of a lower head F, a duraluminum piston rod G, and an upper head H. The lower head was made of phosphor-bronze and contained two leather cup washers lubricated with lanoline, and the upper head was a composite assembly of phosphor-bronze and steel parts containing two cast-iron rings and one leather rings. (Details of this head are not shown in fig. 27.) The driving charge of air was contained in the cylinder I which was sealed by a thin diaphragm J, rigidly clamped as shown. The piston was held in its upper position by a horizontal cast-iron pin K which passed through a turnbuckle L screwed into the piston head. The piston could be brought up firmly against the upper stop, and any desired initial stress placed in the cast-iron pin, by tightening the turnbuckle screw.

An electrically operated sleeve (not shown in fig. 27), adapted to the neck of the air cylinder, was used to shear the diaphragm. The cast-iron pin was snapped as soon as the pressure acted on the upper head, and this occurrence was used to effect the electric opening of the shutter on the pressure-recording camera. Smith had no difficulty in obtaining a very rapid compression but was unable to bring the piston to a dead stop at the end of the stroke without rebound or mechanical fracture, so ultimately he limited his compression time to 0.05 second. He employed many ingenious devices to overcome this defect, but did not make any of them work to his complete satisfaction.

One such device, shown in figure 27 at N, consisted of a collar fitted into an annular recess filled with oil. A small hole was drilled into the recess and fitted with a piece of tubing connected to a reservoir. The impact energy of the piston striking the collar was expended in forcing the oil through the small hole and into the reservoir. This device, however, was not a success.

Smith also found that inertia forces disturbed his optical pressure-recording system, causing relative motion between the light source, indicator mirror, and camera.

He did not develop his machine to the point that it could be used to collect reliable data on combustion, but he did make a valuable contribution to the technique of compression ignition by his efforts.

It is true that many other types of compression machines have been built to study combustion, but these were not suitable for the determination of adiabatic ignition temperatures or delay periods. Among these other types, in which no attempt was made to prevent the piston from moving outward after compression, may be mentioned the compression machine of Duchene (reference 19) which was built to simulate gasoline-engine conditions, and the various other compression machines such as that of Pope and Murdock (reference 20) used to rate Diesel fuels.

APPENDIX B

CONSTRUCTION DETAILS OF THE RAPID COMPRESSION MACHINE

The lower head of the machine (15), containing the combustion cylinder (4), water jacket (16), and mounting flange (17), was machined from a one-piece semisteel casting. (See fig. 1.) The combustion cylinder is 3.681 inches long and 2.002 inches in diameter. The removable head (14) of the combustion cylinder was made from alloy steel and was machined concave on the inner surface to diminish cooling of the contents during and after compression. Any mechanical impact of the piston snout at the end of the stroke is received by a ring (19), clamped between the head and cylinder by a screw plug (18). The ring has an inside diameter of 1.875 inches and was made from mild steel, ground flat on the upper and lower faces. The compression ratio is 14.9 without the ring and could be altered to any lower value by using rings of different thickness. The piston was dimensioned so that, when the skirt (23) is in contact with the lower head (15), there is a clearance of 0.003 inch between the snout and the impact ring.

When the driving and cushion pressures are in proper adjustment, no impression is left on the ring by the snout; thus the snout contacts the ring only very lightly, if at all.

The combustion cylinder is provided with two diametrically opposite ports (20) (only one of which is shown in fig. 1), 0.0625 inch in diameter, through which the combustible mixture is circulated. The ports are closed by the snout immediately after the beginning of the stroke.

Sealing between piston snout and combustion cylinder was accomplished by electroplating a lead band on the end of the snout about 0.375 inch wide and 0.003 inch thick. The piston was then forced into the combustion cylinder by means of a hydraulic jack and any excess lead was sheared off as the snout entered the cylinder. The cylinder was heated to the normal operating temperature, 150° F, before inserting the piston. An excellent fit was obtained in this manner. Tests made to determine the leakage from the combustion chamber showed that the seal was satisfactory. The test procedure is described in the section PRECISION OF PRESSURE MEASUREMENTS.

The piston snout projects 0.681 inch into the combustion cylinder when the piston is at the beginning of the stroke (fig. 1). A part of this space is required for the lead band, part for an annular leak-off groove (35) cut into the combustion cylinder, and the remainder for a gland seal (22).

The gland seal is used to prevent the leakage of nitrogen from the cushion chamber into the combustion cylinder. The seal consists of a neoprene ring, having a 1/4-inch-square cross section and an inside diameter somewhat smaller than the piston snout. The ring is pressed lightly on the piston snout and held in place by a collar (34) secured to the combustion cylinder. Pressure acting on the top and outer face of the ring results in a force which presses the ring firmly into the clearance space between the snout and combustion chamber just above the leak-off groove. The top surface of the neoprene ring is notched radially to allow the pressure to act upon it freely. Any nitrogen which leaks past the gland is led off to the atmosphere by the leak-off groove and two ducts (21), only one of which is shown in figure 1.

The upper part of the snout is 0.010 inch smaller in diameter than the part containing the lead band. This clearance allows a small amount of heavy cup grease to be used on the neoprene ring, for better sealing, without danger of transmitting any of the grease to the combustion chamber walls. The walls have been checked from time to time by wiping with a clean white cloth, but no traces of grease have been found.

The combustion cylinder is surrounded by a water jacket (16) by means of which the initial temperature of the cylinder can be controlled.

The piston was machined from a solid billet of chrome-molybdenum steel and heat treated to a Brinnell hardness of 375. All sliding surfaces were carefully ground. The finished piston weighs 8.25 pounds, which probably represents the minimum weight consistent with the severe duty to which the piston is subjected. The head of the piston snout was dished to a shape similar to the combustion chamber to minimize cooling effects.

A series of 18 ports (10) were machined in the upper part of the piston skirt. These ports register with an equal number of ports (11) in the lower cylinder sleeve (12) when the piston approaches the end of the stroke, thereby releasing the cushion pressure and allowing the driving pressure to hold the piston on its seat.

Effective sealing between skirt and sleeve was accomplished, as in the case of the snout, by electroplating a band of lead about 1/2 inch wide at the bottom of the piston and another about 1/4 inch wide just above the piston ports. Any excess thickness of lead was sheared off when the piston was pressed into the sleeve. A coat of lead about 0.002 inch thick was also placed on the bottom edge of the skirt to diminish the tendency to rebound. The sleeve and piston skirt were lubricated with a thin film of heavy cup grease.

The lower cylinder (2) was machined from a section of centrifugally cast, nickel-steel cannon barrel. The over-all dimensions are 9.855 by 8.977 inches and the bore is 6.875 inches. Eighteen oval ports (24), 7/8 by $2\frac{1}{2}$ inches, were cut in this cylinder about $2\frac{7}{8}$ inches from the bottom. The cylinder is centered on a shoulder in the lower head of the machine and held in place by 16 machine bolts.

The sleeve (12), machined from seamless steel tubing, was press fitted into the lower cylinder. The inside diameter of the sleeve was ground to allow about 0.001 inch clearance for the piston skirt. The sleeve can be raised or lowered to vary the port timing by using different combinations of rings (33) at each end of the sleeve.

The upper cylinder (1) of the machine was made from a piece of seamless steel tubing, 1/2 inch thick, 10 inches long, and with a $5\frac{1}{2}$-inch outside diameter. It was closed at its upper end by a head (25) made from a heavy semisteel casting. The lower end of the cylinder rests on the poppet-valve seat (26) which is clamped between the cylinder and a flange (27). This flange is subjected to great stresses and accordingly was made from a solid billet of chrome-molybdenum steel. These parts are held together by 16 through bolts (28) passing from the head to the lower cylinder. Sealing between the parts was provided by carefully machined surfaces or thin paper gaskets. The head was tapped to receive a 1/4-inch pipe through which the nitrogen is admitted.

The poppet valve and stem were made from cold-rolled steel. The angle of the valve face was $26\frac{1}{2}^{\circ}$ and that of the seat 27°. The valve seat was also made of cold-rolled steel. A stuffing box (29) was provided in the head at the valve stem to prevent leakage. The valve was held closed by one or more shear pins (8), which were placed across two pieces of tool steel. The tool-steel pieces were square in cross section, and rested on a screw jack (7). A piece of half-round hardened drill rod with sharp edges (30) was fitted into the upper part of the hole in the stem and was held in place by a locking pin (31). When the poppet valve was tightened, the entire load fell on the shear pins. Two shear pins of square cold-rolled-steel rod, 1/8 inch on a side, were found sufficient to seal the poppet valve effectively for pressures as high as 600 pounds per square inch.

APPENDIX C

DETAILS OF STRAIN-GAGE CIRCUIT

The strain-gage circuit is shown in figure 5 with the strain-gage unit indicated by the resistance R_{ab}. The unit is simply a pure resistance composed of many turns of fine ("isoelastic") wire on a piece of flat insulating material. (See reference 21.) The unit is cemented onto the stressed member in some suitable manner and as the member deflects under stress, the wire is stretched thereby causing its resistance to increase. If the unit is cemented so that its entire length is stretched with the deflecting member, then the relation between stress and resistance change will be linear and a constant calibration factor can be found for the useful range of the gage.

This calibration factor was determined by measuring the resistance change with a Wheatstone bridge while stressing the cylinder head, to the outside of which the gage was cemented, with definitely known pressures. A special cylinder was constructed for this purpose and provided means of clamping the head in a manner identical with that used when clamping the head in the combustion cylinder. The special cylinder was filled with oil and connected to a dead-weight tester which provided an accurate source of pressure. The strain gage is sensitive to temperature changes and this effect can be very troublesome when performing the calibration. It was offset by making a dummy gage, identical with the original, which was cemented to a block of steel. This dummy gage was used as one arm of the bridge and as the ambient temperature varied, the mass of the block was sufficient to reduce the effect to inconsequential proportions. The calibration factor was thus found to be 5.62×10^{-6} ohms per ohm per pound per square inch for pressures below 800 pounds per square inch.

The change in voltage drop across the gage occasioned by the change in resistance under stress was recorded by the cathode-ray oscillograph and correlated with the change in cylinder pressure. The larger the voltage drop for a given pressure change, the smaller the gain that need be used on the cathode-ray oscillograph amplifiers and the greater the freedom from extraneous electrical interference.

It will be noticed in the circuit diagram of figure 5 that there is a certain amount of resistance in series with the gage and a parallel resistance R_A. The series resistance was used to limit the current through the gage. Neglecting for the moment the parallel resistance, it can be shown that the change in voltage drop across the gage (or "output") for a small change in gage resistance is given by

$$dE_g = \frac{R_1 R_g}{(R_1 + R_g)^2} \times \frac{dR_g}{R_g} \times E$$

where

dE_g change in voltage drop across gage

dR_g change in resistance of gage due to small change in stress

R_g unstressed resistance of gage

R_1 total resistance in series with gage

E impressed electromotive force

The output thus depends on the values of $\frac{dR_g}{R_g}$, the series resistance R_1, and the impressed electromotive force E.

The value of $\frac{dR_g}{R_g}$ is an inherent property of the wire in the gage; that is, a metal giving a large change in resistance with strain will give a large value of $\frac{dR_g}{R_g}$.

It can be shown by differentiation that the quantity $\frac{R_1 R_g}{\left(R_1 + R_g\right)^2}$ is a maximum when $R_1 = R_g$, assuming E is constant. In practice, however, E varies as R_1 is changed and the optimum value of R_1 is most readily determined by trial.

The impressed electromotive force is limited by the ability of the gage to dissipate heat, and serious errors may be introduced by increasing E beyond the limiting value. In this connection it is desirable to have as many effective turns on the gage as possible in order to permit the maximum value of E for a given current.

A strain gage having a resistance of 1000 ohms was used and values of R_1 and E of 5000 ohms and 135 volts were found suitable for this work.

The auxiliary parallel resistance R_A was used to provide a pressure scale on the records. This purpose was accomplished by closing the switch at A whereupon the voltage drop across the strain gage was increased. This voltage drop could be made to represent any pressure by the proper adjustment of the resistances, R_A and R_{cd}. If, then, the switch at A was suddenly closed and opened an instant before the compression of the charge, a square wave with an amplitude representing a definite pressure would be impressed on the record. The closing and opening of the switch was effected in the actual apparatus by the falling weight striking the arm of the contact switch (81) (fig. 2) just before impinging on the poppet valve. The resulting calibration mark is shown in figure 28.

If it is desired to have the calibration mark represent a pressure of, say, 500 pounds per square inch, the resistance in series with the gage is divided into two parts and one of them, R_{cd}, is included in the parallel circuit with R_A. The value of R_{cd} is arbitrary and was made 100 ohms in this circuit. The problem of determining the appropriate value of R_A may then be stated as follows:

Required to find the value of R_A which will make the voltage drop across the strain gage equal for the following two cases:

(1) 500 pounds per square inch on the strain gage R_{ab}; resistance R_A not in circuit.

(2) No pressure on the strain gage; resistance R_A in parallel with resistance R_{cd}.

Let,

m calibration factor for the strain gage, ohms change per ohm of unstrained gage resistance per pound per square inch

and

$M = 500m$, calibration factor in ohms per ohm per 500 pounds per square inch

$Y = 1 + M$

<u>Case (1)</u>

$$R_{ab} = 1000Y$$

The total resistance in the circuit R_T, neglecting the impedance of the oscillograph and the internal resistance of the batteries, is

$$R_T = 5000 + 1000Y$$

The current in the circuit I is

$$I = \frac{E}{R_T} = \frac{E}{5000 + 1000Y}$$

The voltage drop across the strain gage is

$$E_g = IR_{ab} = \frac{1000EY}{5000 + 1000Y}$$

Case (2)

$$R_{ab} = 1000$$

$$R_{cd} = \frac{100R_A}{100 + R_A}$$

$$R_T = \frac{100R_A}{100 + R_A} + 5900$$

The current flowing through the strain gage is

$$I = \frac{E}{R_T} = \frac{E}{\dfrac{100R_A}{100 + R_A} + 5900}$$

The voltage drop across the strain gage is:

$$E_g = IR_{ab} = \frac{1000E}{\dfrac{100R_A}{100 + R_A} + 5900}$$

It is required that for these two cases,

$$E_{g_1} = E_{g_2}$$

where the subscripts indicate cases (1) and (2), respectively.

$$\frac{1000EY}{5000 + 1000Y} = \frac{1000E}{\dfrac{100R_A}{100 + R_A} + 5900}$$

$$R_A = \frac{1}{50} \times \frac{5000 - 4900Y}{Y - 1}$$

It was found experimentally that $m = 5.62 \times 10^{-6}$ ohms per ohm per pound per square inch, so that

$$Y = 1 + 500 \times 5.62 \times 10^{-6}$$
$$= 1 + 2.81 \times 10^{-3}$$

and therefore

$$R_A = 614 \text{ ohms}$$

The same result could have been achieved without using the parallel resistance R_A by momentarily short-circuiting the series resistance R_{cd}. This method would involve a readjustment of the values of the resistances R_{cd} and R_{ef}, of course, and a much smaller value of R_{cd} would be required. It is the difficulty encountered in finding cheap, yet accurate, commercially available resistors of odd values in the low range which renders this method less convenient than the parallel arrangement.

In the present work the pressure scale could not be used as planned because the calibration factor of the gage varied with use. The reason for this variation has not yet been determined.

APPENDIX D

METHOD OF CORRECTING LEAKAGE CURVES FOR

VOLUME OF CONNECTING FITTINGS

It was found that an empirical curve of the form

$$pv^n = c \tag{1}$$

could be fitted to the intermediate leakage curve of figure 8 over a 20-second interval. In this equation,

p absolute pressure

v specific volume

n constant

c constant

At any instant, the rate of change of the mass of gas in volume,

$$V_1 = \text{Volume of chamber} + \text{Volume of connections}$$

will be proportional to some power of the pressure p. Assume the first power, and let ρ be the average density of the gas at any instant; then

$$\frac{d(V_1\rho)}{dt} = c_1\ p$$

or

$$V_1\ \frac{d\rho}{dt} = c_1\ p$$

where c_1 is a constant and t is time.

Also

$$V_1\ \frac{d\left(\frac{1}{v}\right)}{dt} = c_1\ p$$

and from equation (1)

$$\frac{1}{v} = \left(\frac{p}{c}\right)^{\frac{1}{n}}$$

so that

$$\frac{d\left(\frac{1}{v}\right)}{dt} = \frac{1}{n}\left(\frac{p}{c}\right)^{\frac{1}{n}-1} \frac{1}{c}\frac{dp}{dt}$$

and

$$\frac{V_1}{nc}\left(\frac{p}{c}\right)^{\frac{1}{n}-1} \frac{dp}{dt} = c_1 p$$

or

$$(p)^{\frac{1}{n}-2} dp = \frac{n(c)^{\frac{1}{n}} c_1}{V_1} dt$$

Integrating

$$(p)^{\frac{1}{n}-1} = \frac{c_2}{V_1} t + c_3$$

where c_2 and c_3 are constants, c_3 depending on the initial pressure.

Therefore the time to reach a given pressure varies directly as the volume.

In two chambers having volumes V_1 and V_2, the time to reach a certain pressure p will be in the ratio

$$\frac{t_1}{t_2} = \frac{V_1}{V_2}$$

The volume of the combustion chamber when the piston was at the bottom of the stroke was 14.1 cubic centimeters, and the total volume of the chamber and connections was 38.8 cubic centimeters. Therefore the abscissas of the intermediate curve of figure 8 should be reduced in the ratio $\frac{14.1}{38.8} = 0.363$ to give the true curve of leakage. The curve obtained by applying this factor is the lower curve of figure 8.

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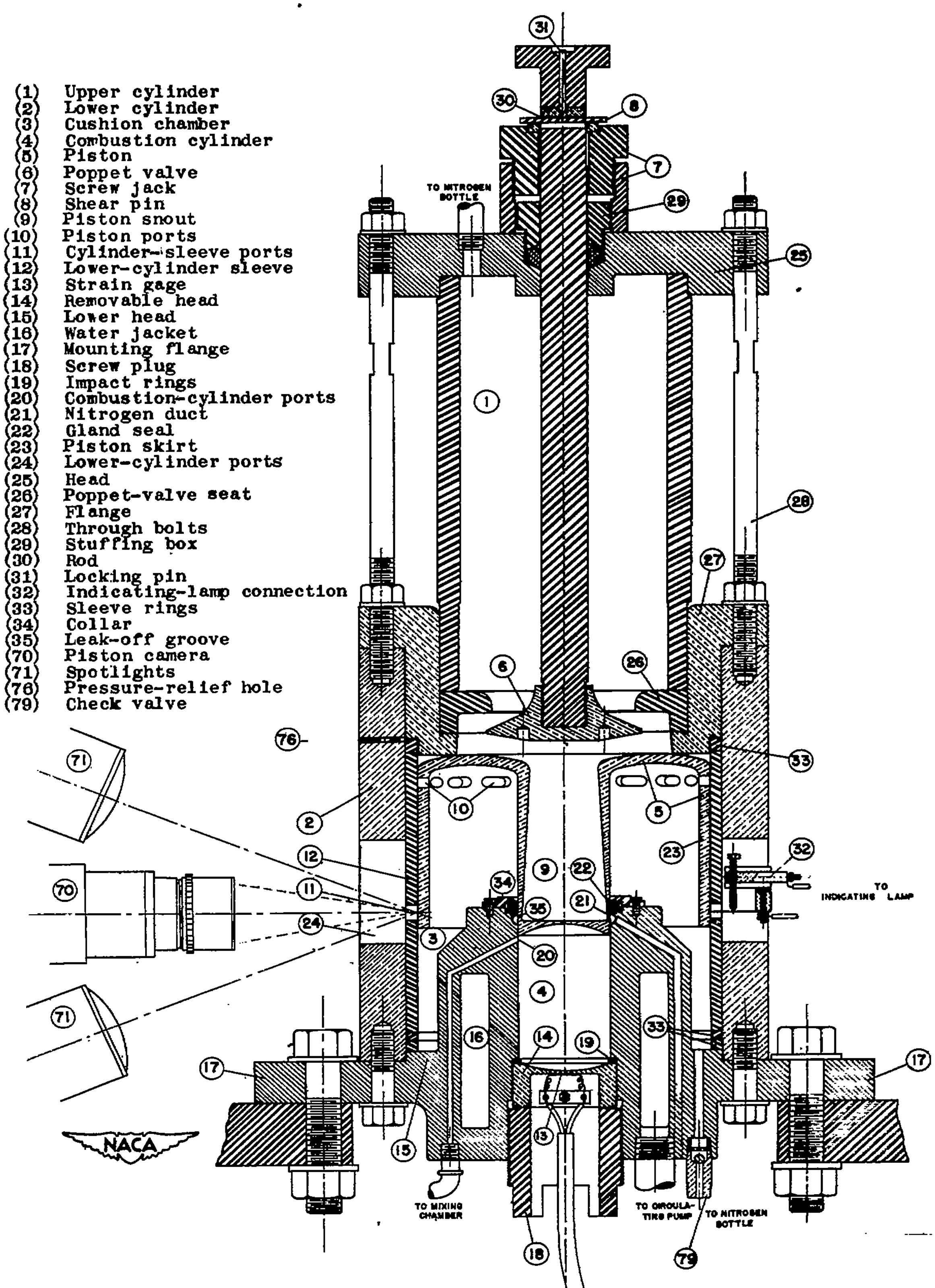

Figure 1.- Sectional view of the M.I.T. rapid compression machine. (For construction details see appendix B.)

(36) Rapid compression machine
(37) Drop weight
(38) Rope bracket
(39) Weight trigger
(41) Rope stop
(42) Rope bracket
(43) Nitrogen cylinder
(44) Driving-pressure gage
(45) Cushion-pressure gage
(46) Jacket-water header tank
(47) Resistance heating units
(48) Thermostat
(49) Connecting pipe
(50) Fuel-air mixing tank
(51) Water circulator pump
(52) Jacket-water thermometer
(53) Steam heat exchanger
(57) Air pump
(58) Drying tower
(59) Humidifier
(60) Wet-air valve
(61) Wet-air valve
(62) Pressure-relief valve
(63) Air filter
(64) Hygrometer
(65) Oscillograph camera
(66) Cathode-ray oscillograph
(67) Solenoid
(68) Oscillograph camera switch
(69) Reference timer switch
(70) Piston camera
(71) Spotlights
(72) Spotlight support
(73) Solenoid
(74) Piston camera switch
(75) False-start indicating lamp
(77) Vacuum pump
(78) Valve
(79) Check valve
(80) Manometer
(81) Pressure calibration switch

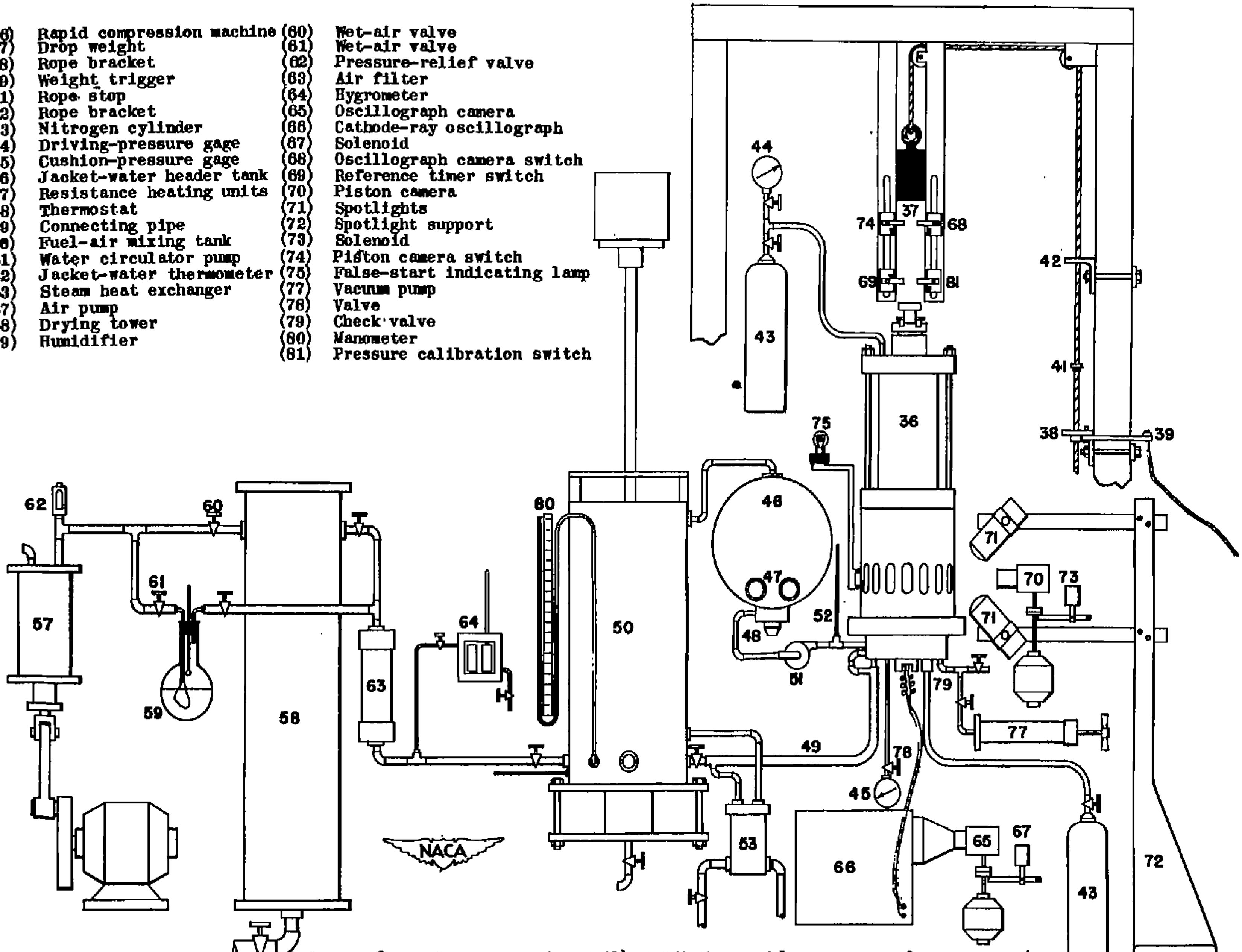

Figure 2.- Components of the M.I.T. rapid compression apparatus.

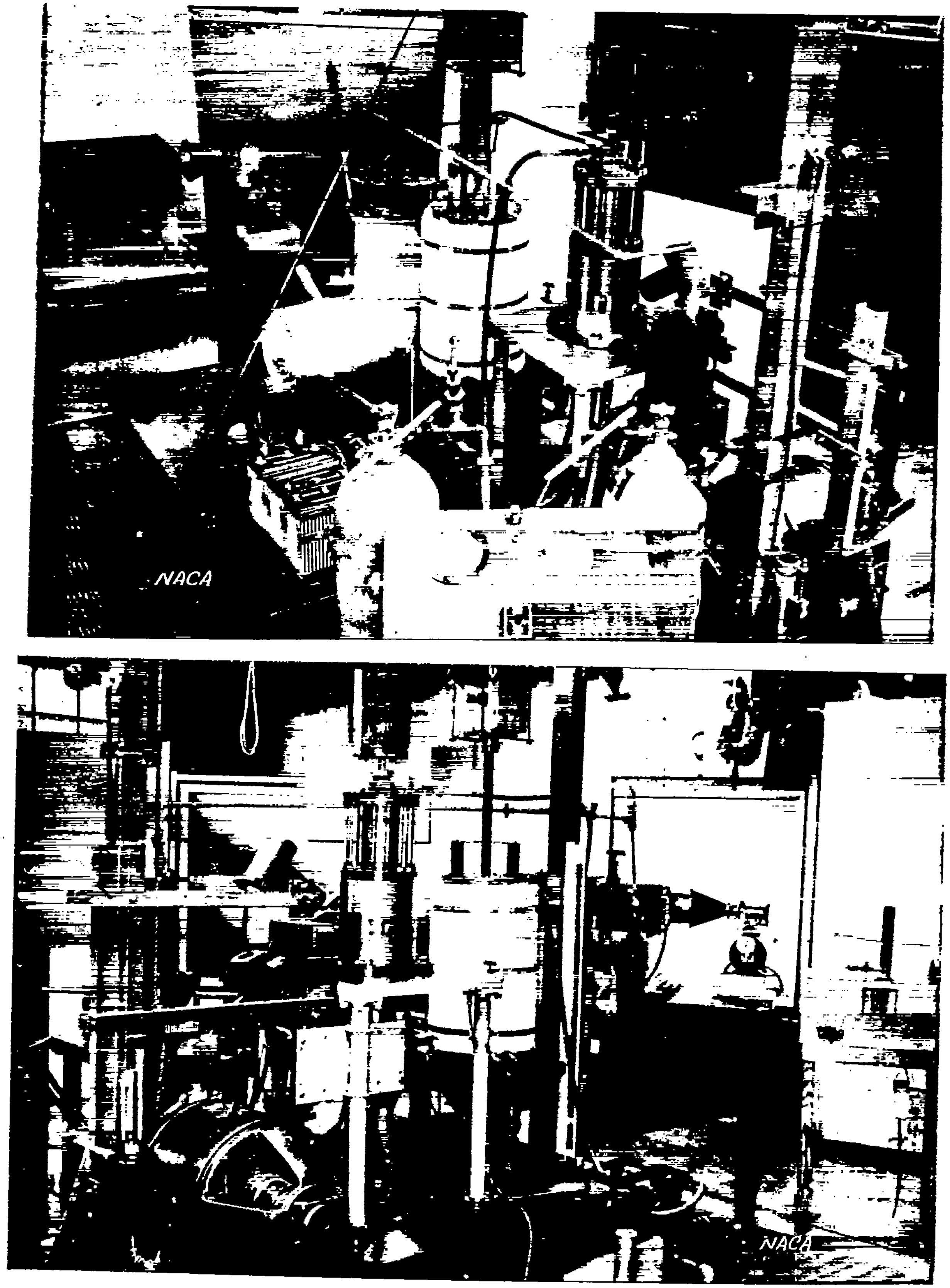

Figure 3.- Photographs of the M.I.T. rapid compression apparatus.

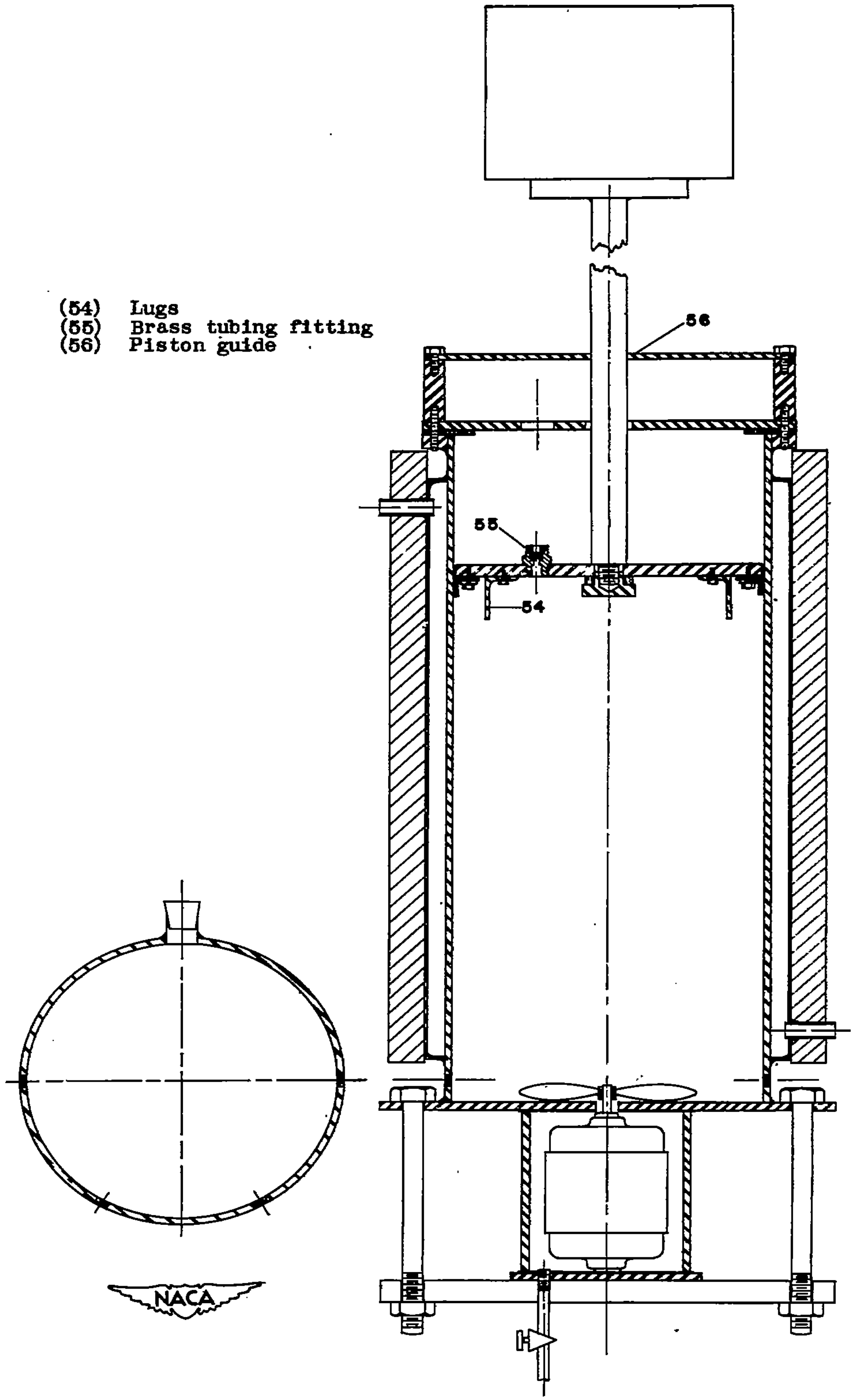

Figure 4.- Cross section of fuel-air mixing tank.

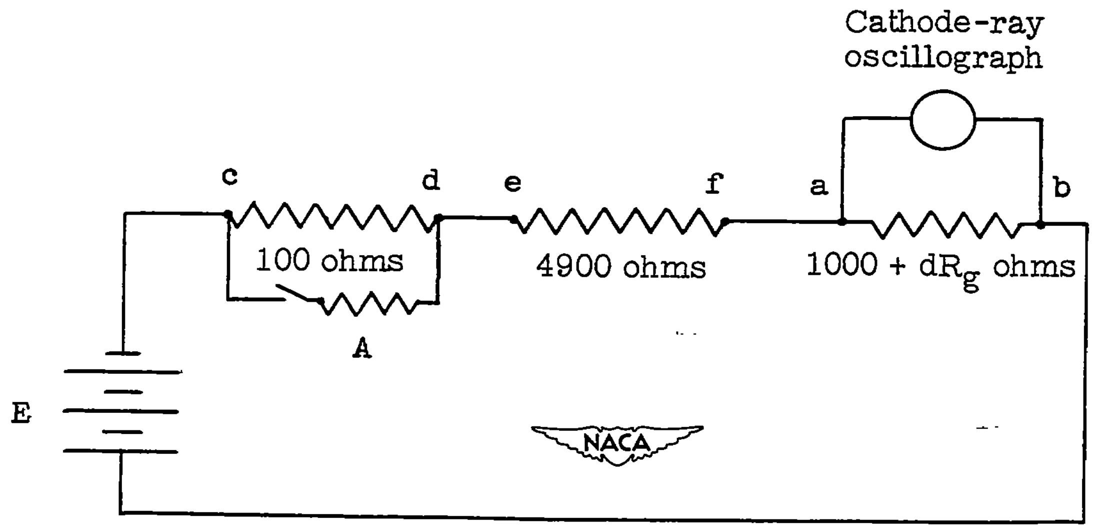

Figure 5.- Strain-gage circuit.

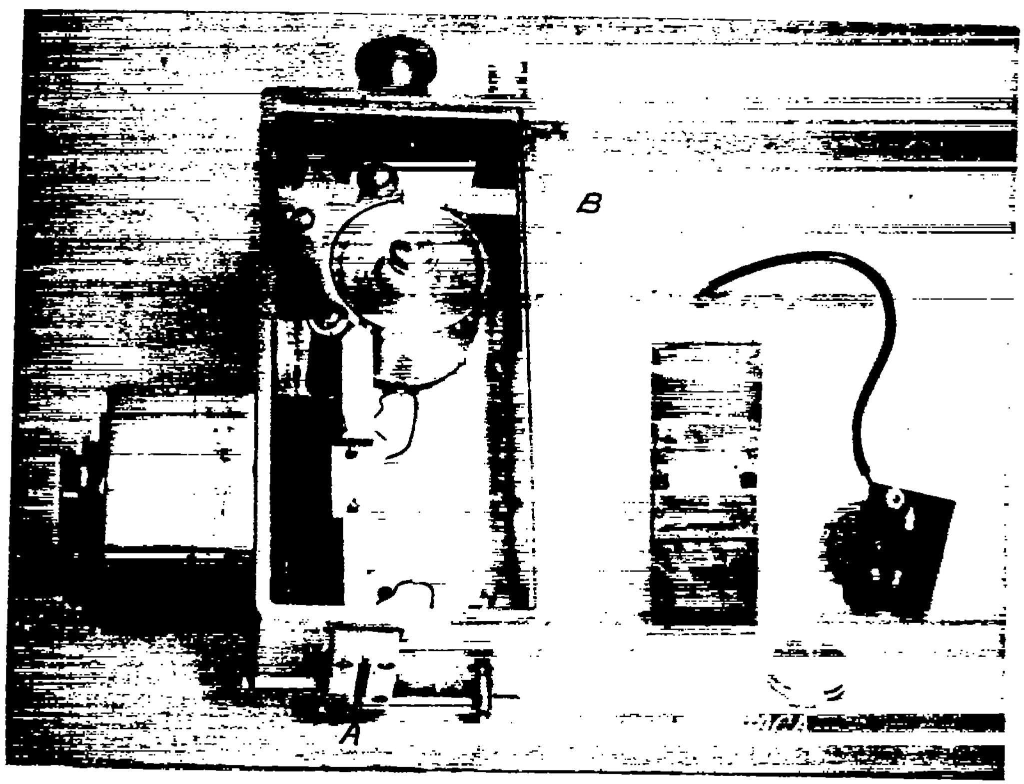

Figure 6.- Details of pressure-recording camera.

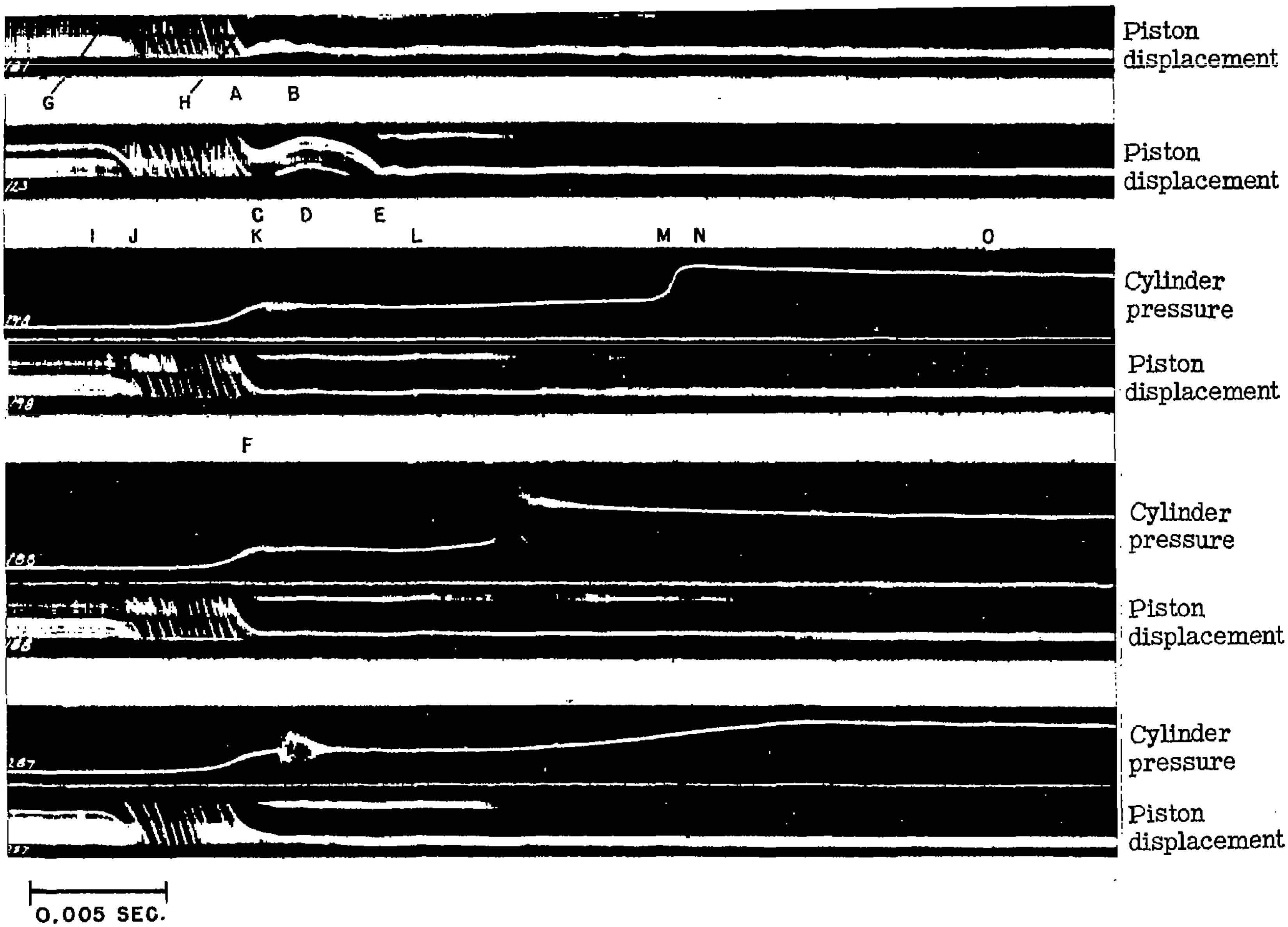

Figure 7.- Specimen records of piston displacement and cylinder pressure obtained with the M.I.T. rapid compression machine.

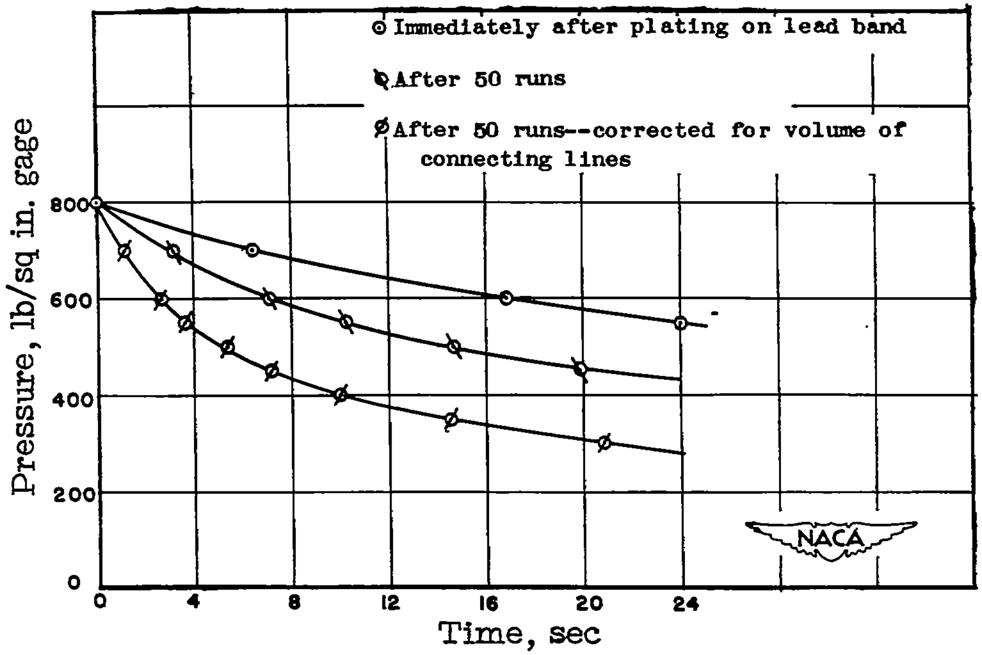

Figure 8.- Leakage curves; change in combustion-chamber pressure with time.

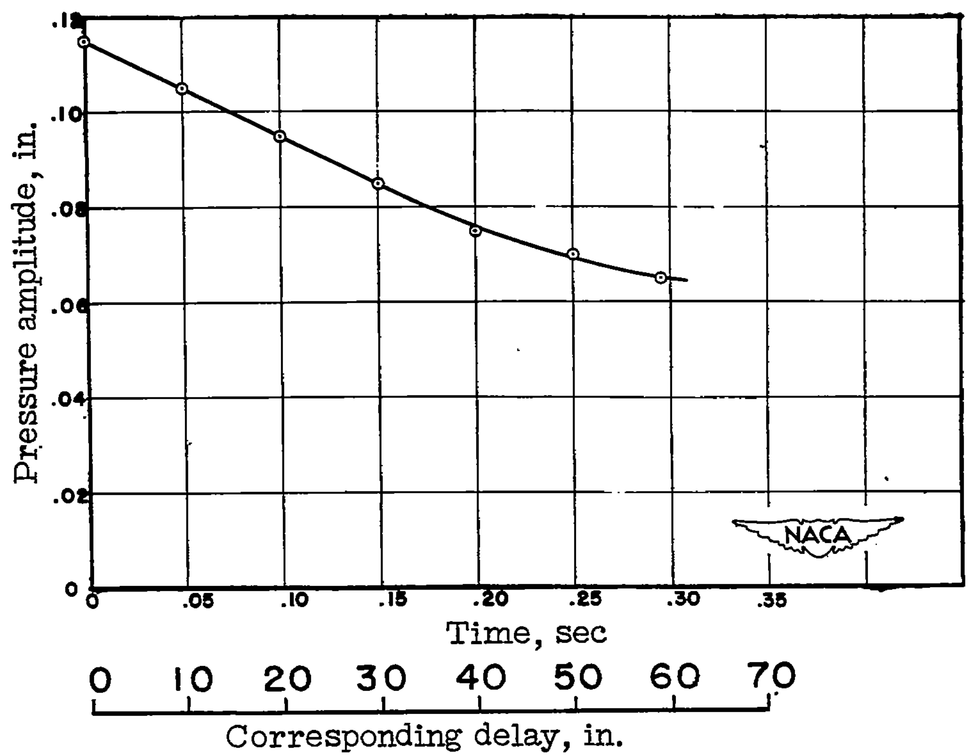

Figure 9.- Results of heat-loss test showing drop in compression pressure with time. Pressure is measured in terms of cathode ray-oscillograph response.

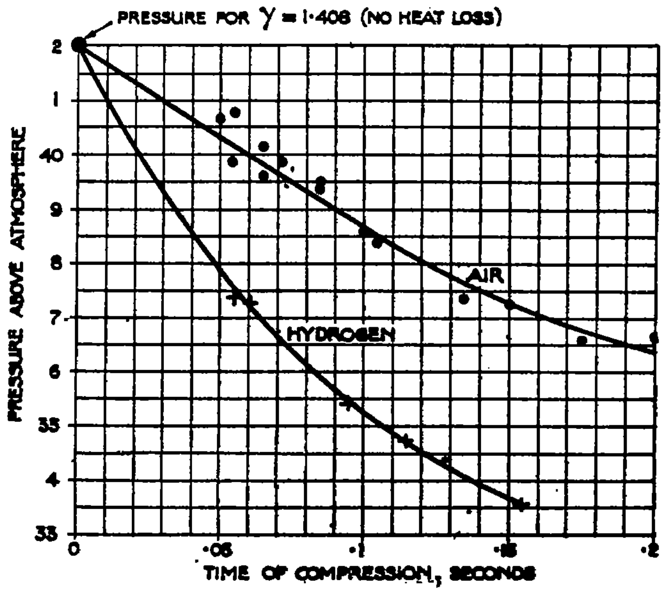

Figure 10.- Pressure-time curves for air and hydrogen obtained by Tizard and Pye to demonstrate heat losses. (From reference 5.)

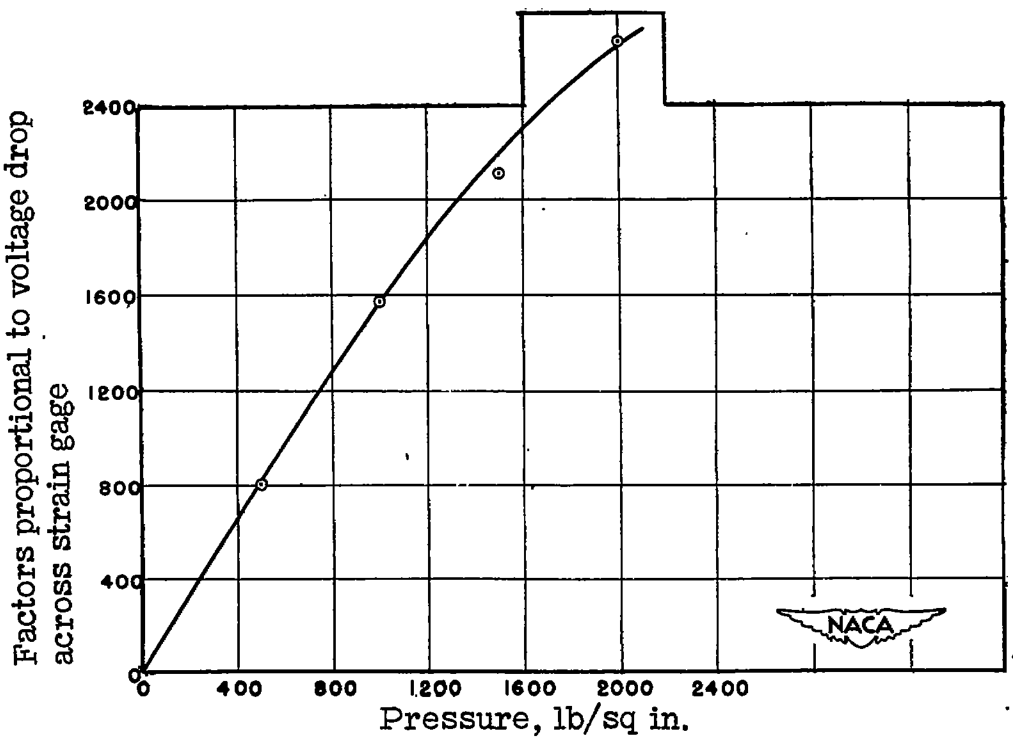

Figure 11.- Calibration curve for strain gage and cylinder head unit.

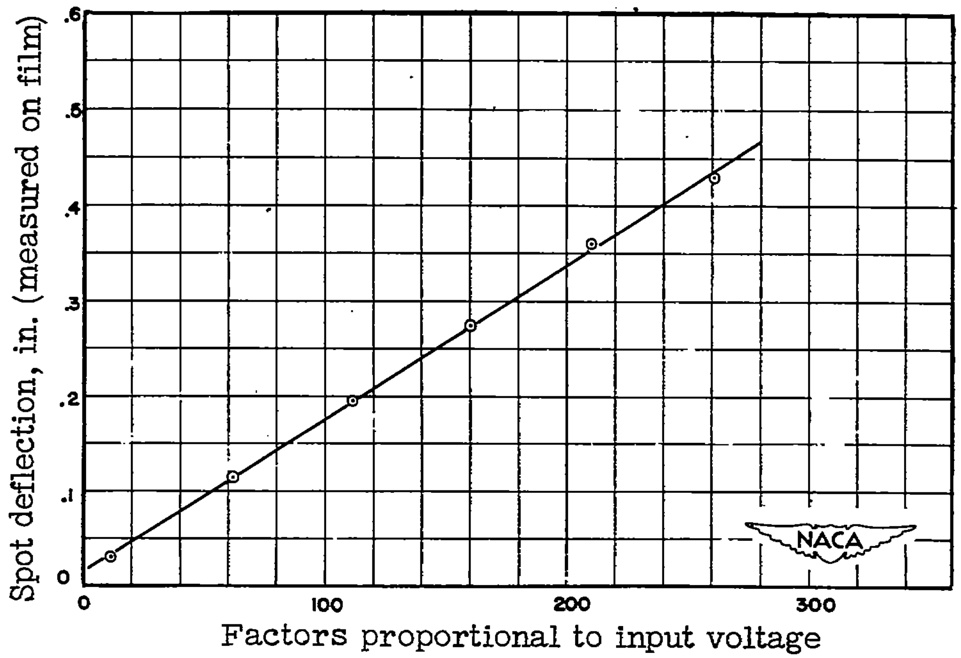

Figure 12.- Over-all response of oscillograph-optical system to suddenly applied voltage.

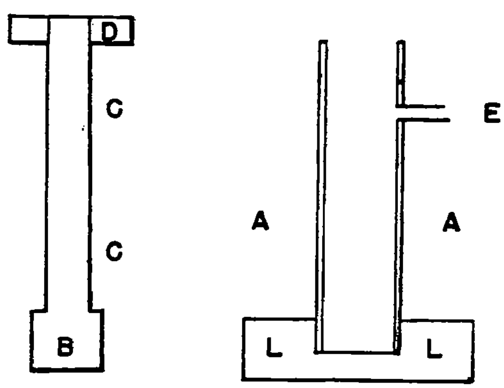

Figure 13.- Sketch of Falk's original apparatus. (From reference 8.)

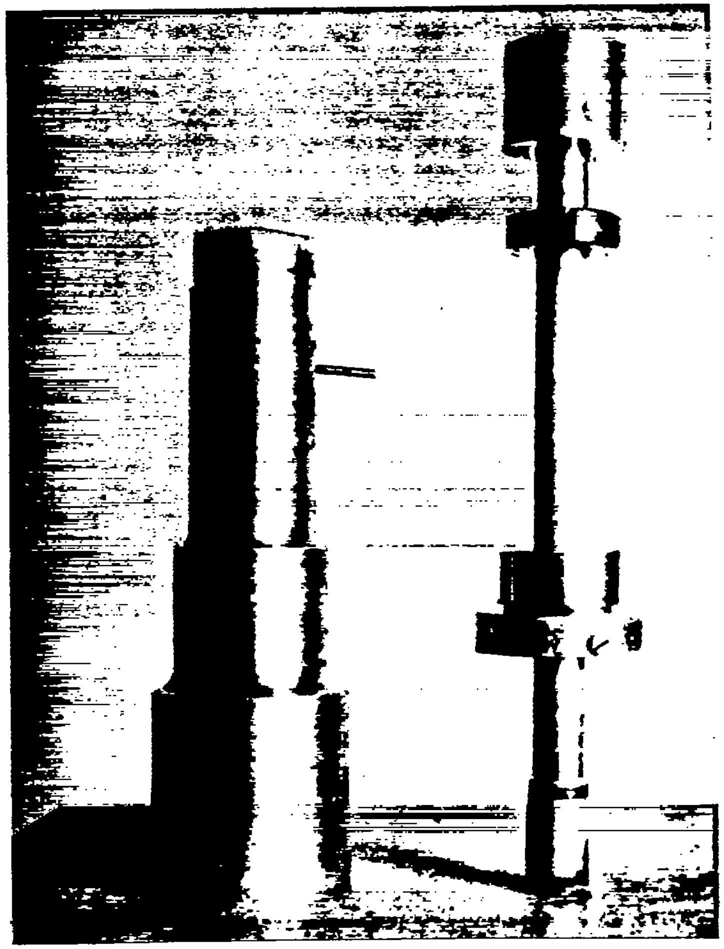

Figure 14.- Photograph of Falk's improved apparatus. (From reference 9.)

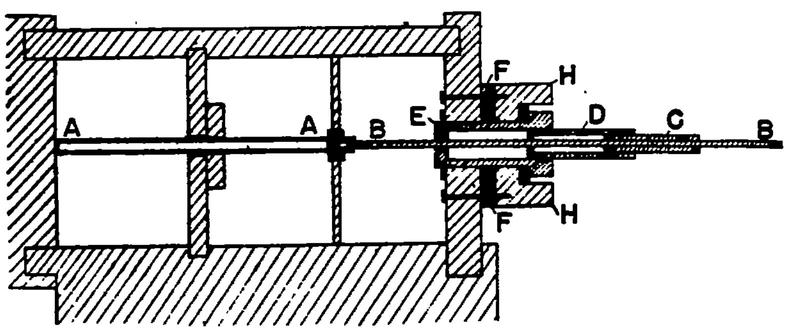

Figure 15.- Cross section of apparatus used by Dixon, Bradshaw, and Campbell. (From reference 10.)

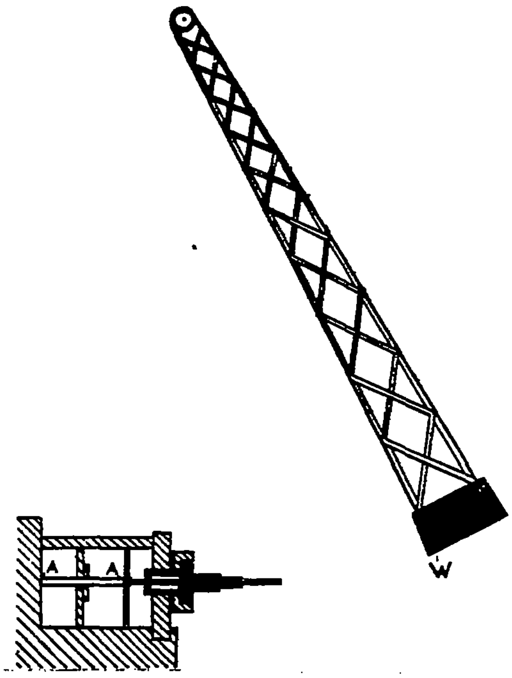

Figure 16.- Pendulum arrangement used by Dixon, Bradshaw, and Campbell. (From reference 10.)

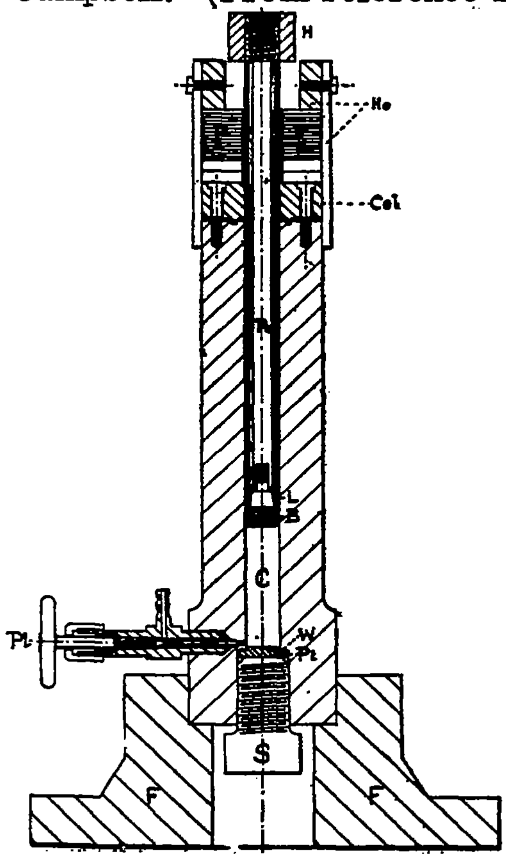

Figure 17.- Compression machine used by Dixon and Crofts. (From reference 11.)

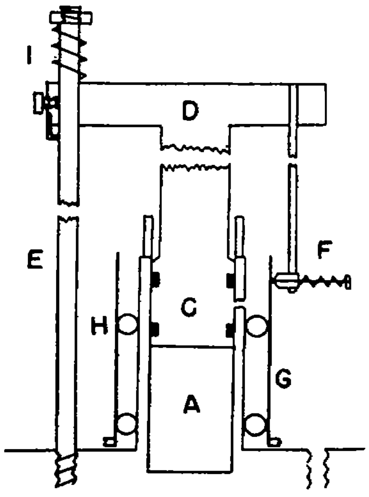

Figure 18.- Details of Cassel's machine. (From reference 12.)

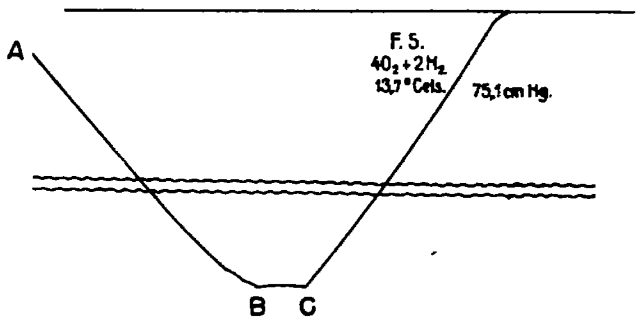

Figure 19.- Record of piston motion obtained by Cassel. (From reference 12.)

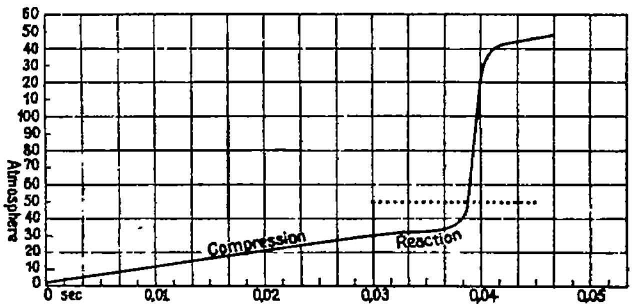

Figure 20.- Pressure-time curve of compression ignition computed by Cassel. (From reference 12.)

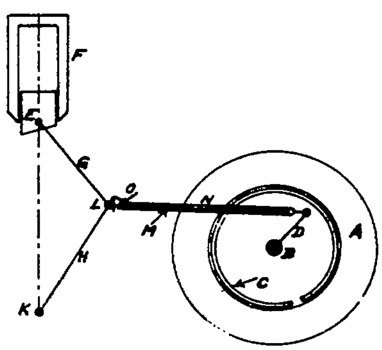

Figure 21.- Details of compression machine used by Tizard and Pye. (From reference 14.)

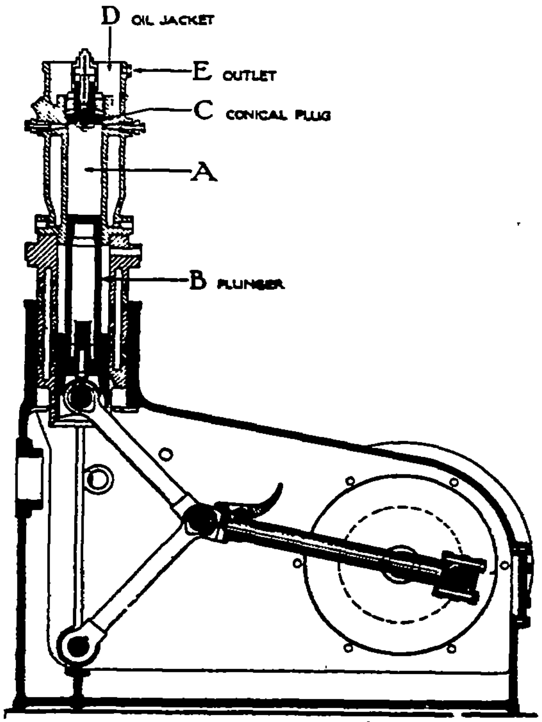

Figure 22.- Tandem cylinder compression apparatus of Tizard and Pye. (From reference 5.)

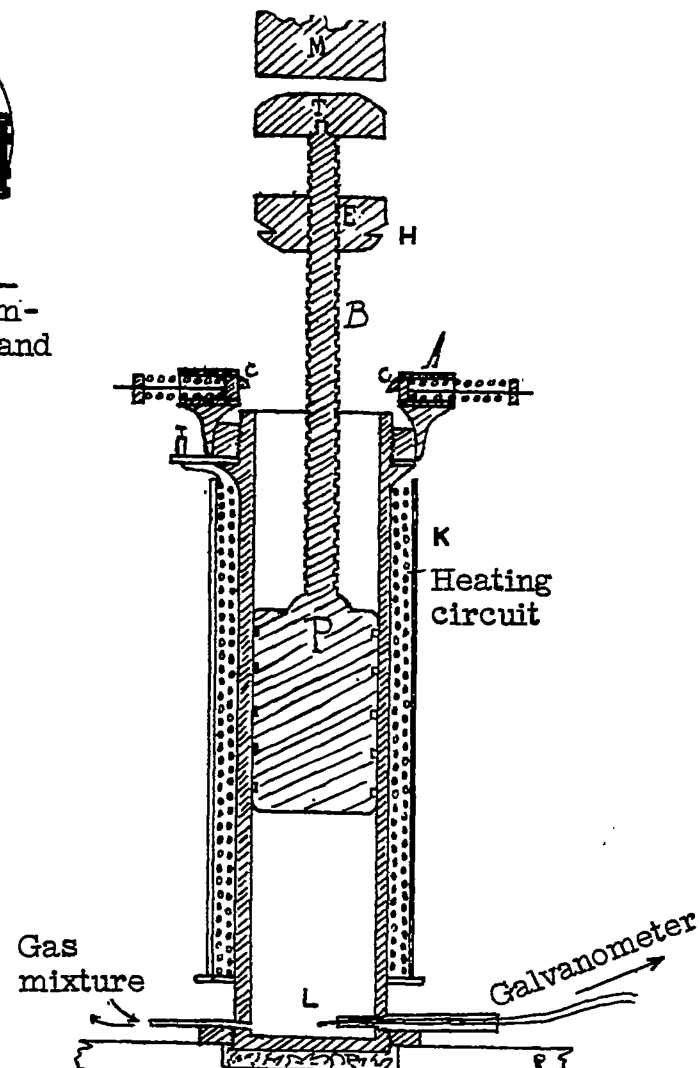

Figure 23.- The compression machine of Pignot. (From reference 15.)

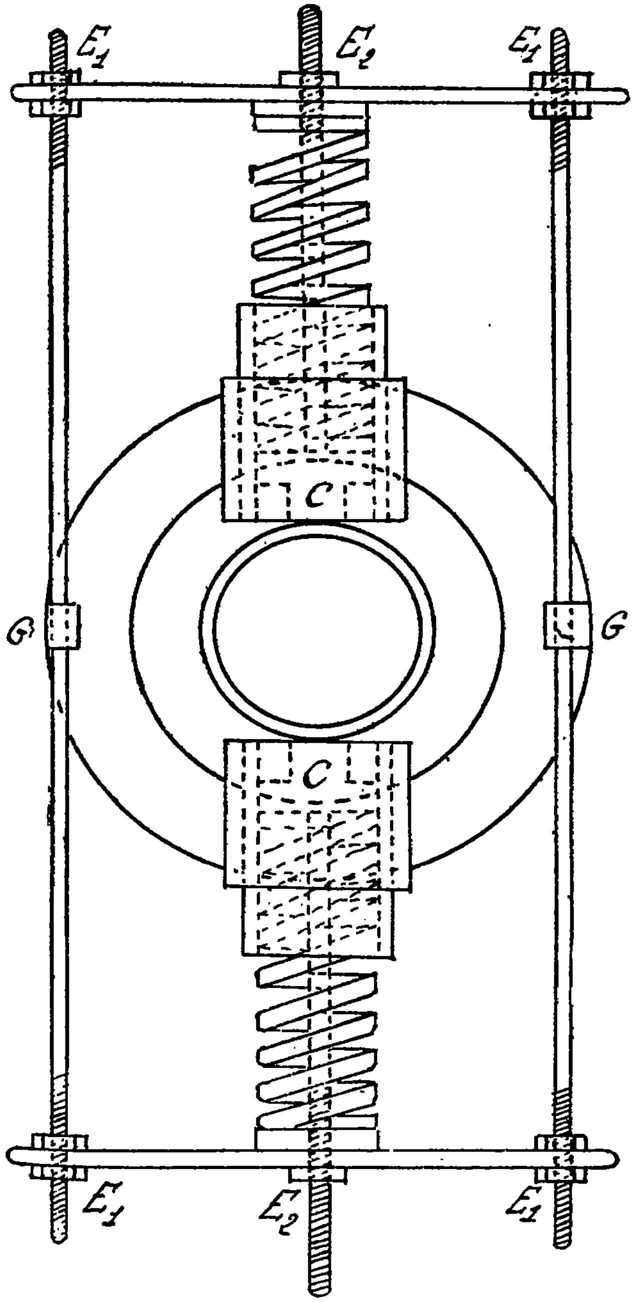

Figure 24.- Detail of the clamping mechanism of Pignot's machine. (From reference 15.)

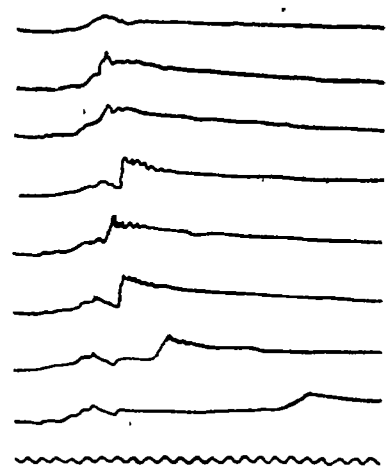

Figure 25.- Pressure-time explosion records obtained by Aubert and Pignot. (From reference 16.)

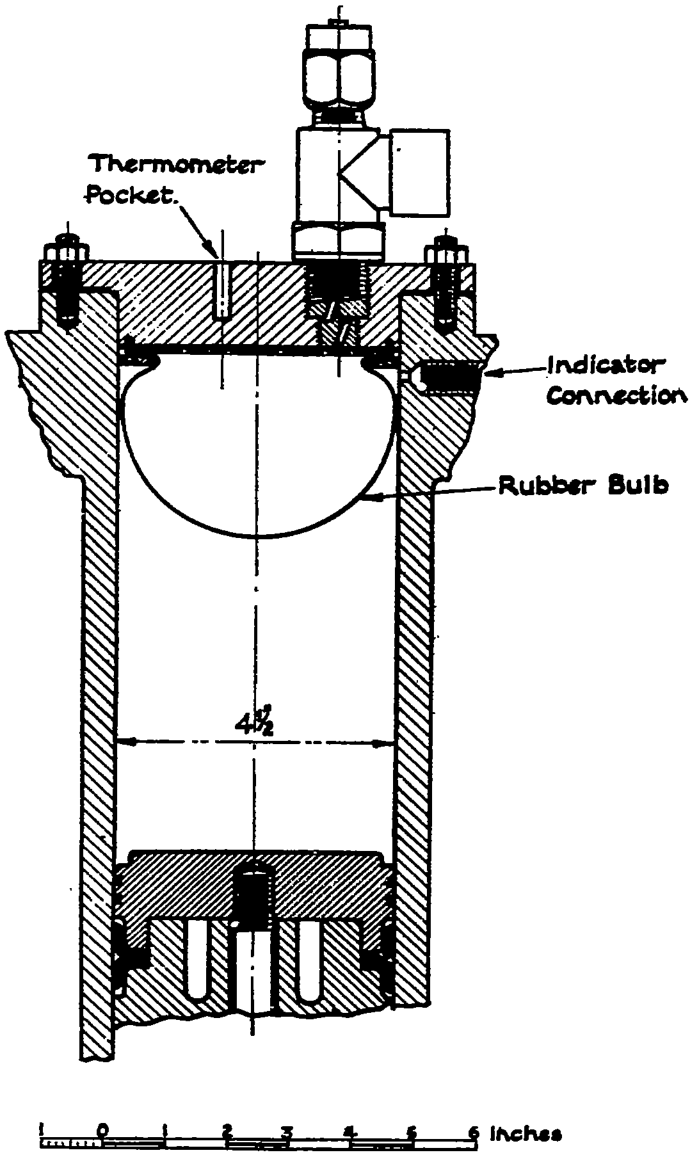

Figure 26.- Fenning and Cotton's adaptation of rubber bulb to compression machine of Tizard and Pye. (From reference 17.)

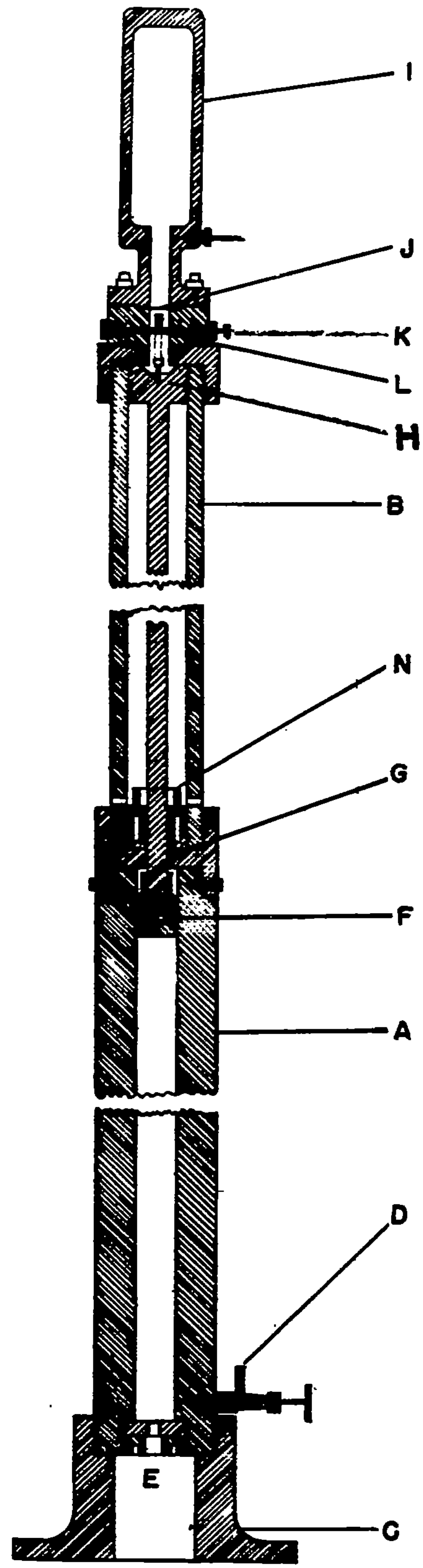

Figure 27.- Compression machine developed by V. C. Smith. (From reference 18.)

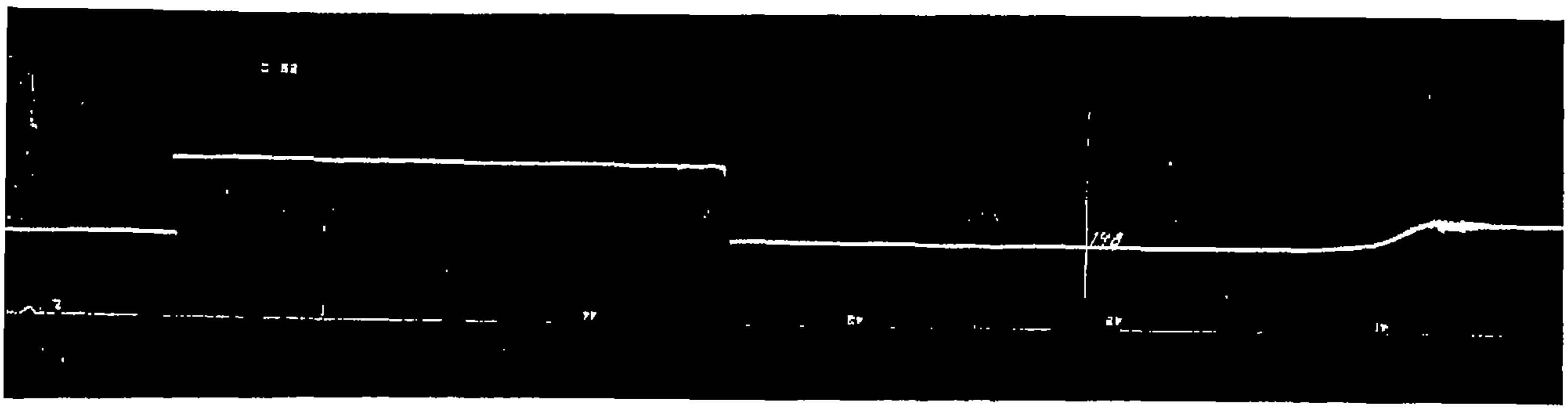

Figure 28.- Specimen record showing electrically determined pressure scale.